NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

BOILING OF HIGHLY WETTING LIQUIDS IN OSCILLATORY FLOW

by

Ugur Turk

December 1995

Thesis Advisor: M. D. Kelleher

Approved for public release; distribution is unlimited.

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE December 1995	3. REPORT TYPE AND DATES COVERED Master's Thesis

4. TITLE AND SUBTITLE **BOILING OF HIGHLY WETTING LIQUIDS IN OSCILLATORY FLOW**

5. FUNDING NUMBERS

6. AUTHOR(S) Turk, Ugur

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey CA 93943-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(maximum 200 words)*

In the present study, boiling of highly wetting dielectric fluid has been investigated in an oscillating fluid environment. A piston is designed to create oscillations in the fluid and over a heated platinum wire. Because of their low surface tension, these liquids require very high superheat to initiate nucleate boiling. It is expected that the amount of necessary temperature overshoot for the onset of nucleate boiling, can be decreased with oscillation in the fluid. The oscillation can remove the bubbles, which are forming in the nucleation sites as soon as they start growing on the outer surface. This increases efficiency of nucleation sites, which are very scarce.

All of the oscillation amplitudes and frequencies, tested here, changed the boiling curve of highly wetting dielectric fluid, so that the apparent temperature overshoot has decreased. Remarkably at some oscillation amplitude and frequencies the superheat is almost vanished. The effects of the amplitudes and frequencies on the boiling curve varied because of the present bubble size and growth rate, which depend on the size and shape of the nucleation sites.

14. SUBJECT TERMS Boiling in dielectric fluids

15. NUMBER OF PAGES 99

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18 298-102

BOILING OF HIGHLY WETTING LIQUIDS IN OSCILLATORY FLOW

Ugur Turk
Lieutenant Junior Grade, Turkish Navy
B.S., Turkish Naval Academy, 1989

Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
December 1995

Author: Ugur Turk
Ugur Turk

Approved by: Matthew Kelleher
Matthew D. Kelleher, Thesis Advisor

Matthew Kelleher
Matthew D. Kelleher, Chairman
Department of Mechanical Engineering

ABSTRACT

In the present study, boiling of highly wetting dielectric fluid has been investigated in an oscillating fluid environment. A piston is designed to create oscillations in the fluid and over the heated platinum wire. Because of their low surface tension, these liquids require very high superheat to initiate nucleate boiling. It is expected that the amount of necessary temperature overshoot for the onset of nucleate boiling, can be decreased with oscillation in the fluid. The oscillation can remove the bubbles, which are forming in the nucleation sites as soon as they start growing on the outer surface. This increases efficiency of nucleation sites, which are very scarce.

All of the oscillation amplitudes and frequencies, tested here, changed the boiling curve of highly wetting dielectric fluid, so that the apparent temperature overshoot has decreased. Remarkably at some oscillation amplitude and frequencies the superheat is almost vanished. The effects of the amplitudes and frequencies on the boiling curve varied because of the present bubble size and growth rate, which depend on the size and shape of the nucleation sites.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

Symbol	Unit	Description
$A_{Amplitude}$	mm	Oscillation Amplitude
$A_{Pt.Wire}$	m^2	Wire Surface Area
a	in	Main Chamber Inner Length
b	in	Main Chamber Inner Width
C_p	J/kg °C	Specific heat
D_{Piston}	in	Piston Diameter
$D_{Pt.Wire}$	mm	Wire Diameter
f	Hz	Oscillation Frequency
$I_{2\Omega}$	A	Precision Resistor Current
$I_{Pt.Wire}$	A	Platinum Wire Current
k	W/m°C	Thermal conductivity
$L_{Pt.Wire}$	mm	Wire Length
L_{Stroke}	in	Piston Stroke Length
Q	W	Power
q''	W/ m^2	Heat Flux
$R_{2\Omega}$	Ω	Precision Resistor
$R_{Pt.Wire}$	Ω	Platinum wire resistance
T_{bulk}	C	Fluid bulk temperature
T_{cond}	C	Condenser Temperature
T_{film}	C	Film Temperature
T_{Period}	s	Oscillation Period
T_{surf}	C	Wire Surface Temperature

$V_{2\Omega}$	V	Precision Resistor Voltage Drop
$V_{Pt.Wire}$	V	Platinum Wire Voltage Drop
α	m²/s	Thermal diffusivity
β	1/°C	Thermal expansion coefficient
ρ_l	kg/m³	Liquid density
ν	m²/s	Kinematic viscosity
Δ_{Piston}	mm³	Piston displacement

UNCERTAINTIES:

$\omega_{A,Amplitude}$	mm	Uncertainty in Oscillation Amplitude
$\omega_{A,Pt.Wire}$	m²	Uncertainty in Wire Surface Area
ω_a	in	Uncertainty in Main Chamber Length
ω_b	in	Uncertainty in Main Chamber Width
$\omega_{D,Piston}$	in	Uncertainty in Piston Diameter
ω_D	mm	Uncertainty in Wire Diameter
ω_f	Hz	Uncertainty in Oscillation Frequency
ω_L	mm	Uncertainty in Wire Length
$\omega_{L,Piston}$	in	Uncertainty in Piston Stroke
ω_Q	W	Uncertainty in Power
$\omega_{q''}$	W/ m²	Uncertainty in Heat Flux
$\omega_{R,2\Omega}$	Ω	Uncertainty in Precision Resistor
ω_{TC}	C	Uncertainty in Thermocouple Temperature
$\omega_{T,Period}$	s	Uncertainty in Oscillation period
ω_{Tsurf}	C	Uncertainty in Wire Surface Temperature
$\omega_{V,2\Omega}$	V	Uncertainty in Precision Res. Voltage Drop

$\omega_{V,Pt.Wire}$	V	Uncertainty in Pt.Wire Voltage

DIMENSIONLESS NUMBERS:

Pr	Prandlt number
Ra_D	Rayleigh number
$\overline{Nu}_D$	Nusselt number

ACKNOWLEDGMENTS

The author would like to express his gratitude to Professor M. D. Kelleher for his highly experienced guidance, advice and support towards completion of this thesis.

He wishes to thank the members of the Mechanical Engineering Support Shop for their efforts. Specially thanks to Mr. Jim Scholfield whose expertise technical support was invaluable.

I. INTRODUCTION

A. BACKGROUND

The developments in electronics and computer technology have led to higher packaging densities of computer chips. As a result of these developments the power dissipation of the computer chips has increased as well. In order to achieve lower failure rates during operation, longer life times and lower maintenance costs, electronic equipment must be cooled. If cooling is not sufficient, the reliability of electronic equipment will decrease. Because of inefficient cooling, component temperatures may exceed the limiting values, which is of the order of 85 C for most of electronic components.

For quite a long time natural and forced convection cooling with air have been implemented as solutions to the electronics cooling problem. The disadvantages of these methods and increasing need for better cooling with super computers has led the way to immersion cooling with liquids. Immersion cooling is a method to deal with the levels of heat flux and volumetric heat generation, which are characteristics of high performance computers. This cooling technique has two distinctive advantages. First liquids as coolants are more effective due to higher heat capacities than gasses. Secondly cooling with liquids has the capability of two phase boiling heat transfer. During boiling, latent heat can extract enormous amounts of heat from electronic components.

Two phase heat transfer in immersion cooling can provide higher heat fluxes and more uniform temperature distributions for an array of computer chips. Chu and Agonafer [Ref. 1] report that water can not be used in spite of its suitable heat transfer properties in direct immersion cooling. The best choice is dielectric fluids like fluorocarbons, which are also compatible with semiconductors.

The research on electronic cooling with dielectric liquids like fluorinerts (FC series of 3M corporation) is still going on. The FC-72 used in this work series is non-corrosive, dielectric and has a relatively low saturation temperature of 56 C. Liquid evaporation

cooling can handle heat fluxes between 5 - 120 W/cm^2 [Ref. 2]. The peak heat flux for fluorinerts of 3M corporation [Ref. 3] for pool boiling is about 12 - 15 W/cm^2.

Boiling with fluorinerts like FC-72 has some problems. FC-72 has very low surface tension, which means almost zero wetting angle. This fluid can fill in even the smallest pits and cavities, eliminating most of the nucleation sites on the surface, which are necessary for the onset of boiling. As a result of the absence of nucleation sites, the surface temperature departs from the saturation temperature significantly during boiling, which causes wall superheat. The surface temperature excursion during boiling due to the heat flux is the core of the problem. Absence of nucleation sites delays nucleate boiling and causes higher surface temperatures.

Two techniques are under investigation to reduce the amount of excessive superheat required to initiate nucleation boiling for practicable applications of fluorinated hydrocarbons as dielectric cooling liquids in two phase immersion cooling. First surface properties and surface treatment can be selected such that the number of available nucleation sites is relatively higher. Second increasing the physical activities on the hot surface is expected to reduce the surface tension effects and enhance nucleate boiling.

Surface materials and treatments, which provide more nucleation sites in the right range, reduce wall superheat and increase critical heat flux. Unfortunately with today's technology it is not very likely to get more nucleation sites in the right size range without damaging the computer chip itself by surface treatment.

Instead of improving surface properties, it is possible to decrease the amount of superheat, by enhancing nucleate boiling by means of physical modifications. Different methods of bubble pumping to decrease the effects of surface tension and detach the bubbles forming on the hot surface have been investigated.

In the present study, a platinum wire is calibrated to read temperatures in pool boiling of FC-72. A sinusoidal motion is created by a piston in the fluid. It is expected that the motion of the fluid will detach the bubbles, which form on the platinum wire surface and decrease the amount of superheat necessary to initiate boiling.

B. PREVIOUS WORK

You [Ref. 4] has conducted tests which have shown that the diameter of the bubbles required for the onset of nucleate boiling on highly wetting dielectric fluids like FC-72, is 0.05-0.1μm.

You, Bar-Cohen and Simon [Ref. 5] conducted experiments with cylindrical heater surfaces immersed in FC-72 and R-113, saturated at one atmosphere pressure. They have observed the effects of fluid and surface properties and materials on boiling regimes and the onset of nucleate boiling. They have found that incipience wall superheat reduced about 25 C and nucleate boiling superheat decreased about 6 C in FC-72 compared to R-113. They have concluded that the fluid properties are more effective on boiling curve than surface material and FC-72 is more advantageous for cooling than R-113.

You, Simon and Bar-Cohen [Ref. 6], studied enhanced surfaces with more available nucleation sites in immersion cooling with boiling. The study showed that a particle layering technique, which could be applied to computer chips without damage or stress, lowers the wall superheat in boiling and increases critical heat flux compared to the untreated surface.

Marcellus [Ref. 7], conducted experiments to show that forced flow can increase the critical heat flux value by rapid removal of vapor bubbles from the surface. A peak heat flux value of 78 W/cm^2 with FC-75 has been achieved, when the fluid velocity was 7 ft/sec.

Recently, Kelleher, Egger Joshi and Lloyd [Ref. 8] conducted experiments on a vertical array of five horizontal platinum wires. They have observed that a temperature overshoot is necessary to initiate nucleate boiling in highly wetting dielectric liquids. They have conducted some experiments to determine the effect of the bubbles coming from the lower wires on the incipience of nucleation boiling on the surface of the upper wires. Their results show that the bubbles from the upstream source reduced the temperature overshoot on a downstream surface. They have used FC-72 as the dielectric fluid in their experiments.

C. OBJECTIVES

The purpose of this experimental study is to achieve superheat reduction by forcing bubbles to depart from the hot surface with the help of fluid motion which overcomes surface tension effects. Departing bubbles provide the nucleation sites for new bubble formation and give way to nucleate boiling. The fluid motion is created in FC-72 by piston displacement. Different piston stroke lengths and frequencies should be tested to see the temperature excursion on the wall.

II. EXPERIMENTAL APPARATUS

A. DESCRIPTION OF COMPONENTS (Figure 1)

The experimental setup consists of four main parts: the main chamber; the front chamber; the adjustable stroke piston; and DC motor. The main chamber has been used in the previous experiments to investigate the boiling of FC-72 under different circumstances and is modified to be used for this study. The goals of this experiment required some modifications, which are the design of the adjustable stroke piston, DC motor and the front chamber. The front chamber regulates the motion in the fluid, which is caused by the piston, and transmits the motion to the main chamber. Figures 2a and 2b show a different view of experimental apparatus and its schematic drawing.

The main and the front chambers hold the dielectric fluid FC-72. To prevent lose of FC-72 during degassing, sealing is very important. At every connection point, RTV Silicone Adhesive Type 1 is used as a sealant. At the clearance between the piston seal and the front chamber, teflon tape is utilized to prevent leakage.

1. Main Chamber (Figure 3)

The main chamber is a Plexiglas box with an aluminum cover on the top. The inner dimensions of the main chamber are 5.9964 x 2.3776 x 5.9843 in. (Figure 4a). This measurement is necessary to calculate the displacement of the fluid in the chamber and the amplitude of the motion during the experiments with the piston running at a given stroke length.

The board, on which the 0.05 mm platinum wire is attached with an adjustable spring system, can be placed in and removed from the chamber by means of two slots on the side walls. In order to connect the heaters and the platinum wire to their power supplies and the thermocouples to the data acquisition system, a tube (Figure 3) at the back wall of the chamber is used. All the wiring necessary for the equipment in the main chamber exits via this tube and goes either to the connection board or to the data acquisition system.

In order to reduce buoyancy induced convection from the bulk heaters one strip heater was used to maintain the FC-72 close to saturation temperature. When the experiment were conducted close to the saturation temperature, heat losses were critical. Because of this the main and the front chambers both are covered by two layers of insulation to decrease the heat losses.

Four thermocouples in the main chamber read the bulk temperature of the FC-72. The passage between the front chamber and the main chamber is an oval opening and the front chamber side of the opening is covered with a flow regulator, to provide uniform flow from the front chamber to the main chamber.

The main chamber contains three important parts: the condenser; the bulk heaters; and the board with the adjustable spring system.

a. Condenser (Aluminum Cover Plate) (Figures 4a, 4b and 5)

The main chamber is covered by an aluminum plate, which condenses FC-72 vapor and returns it to the chamber. The aluminum plate is fixed to the chamber by 8 screws, which apply required pressure on the O-ring at the same time. As it has been mentioned, for additional insulation this connection part is covered with RTV sealant. The lower surface of the cover plate has 4 thermocouples embedded in a cross shaped groove, (Figure 4a) which read the condenser surface temperature.

On the upper surface of the condenser (Figures 4b and 5), there are three thermo-electric coolers connected in parallel, which are manufactured by MELCOR THERMOELECTRICS [Ref. 9]. They keep the condenser temperature below saturation. These coolers are adjustable to certain range of temperature differences. They are controlled by current, because the voltage drop across the thermo-electric coolers changes non-linearly with temperature. The thermo-electric cooler in the middle is connected to a toggle switch, which is another alternative to control the condenser temperature.(Figure 6)

CP 1.4-127-045L type thermo-electric cooler have been used. These have an operating point of ; I = 8.5 Amps, V = 15.4 Volts, and the dimensions are 40 x 40 x 3.3

mm. The CP series of this type of cooler provides larger heat pumping applications for higher currents. The thermo-electric coolers are operated at 5 A in parallel.

To keep the cold side surface at about 20 C, the hot surface is equipped with an aluminum finned heat sink and air is blown between the fins by a fan. This helps to provide the lower and the upper limits of the temperature difference on the cold and hot sides as low as possible.

b. Heaters

Three strip heaters are used to provide the required bulk heating during degassing and experimentation. The heaters are fixed to a very thin aluminum plate which is at the bottom of the main chamber. There are two main purposes of heating in this experiment. Firstly, the air dissolves up to 48% [Ref. 10] by volume in FC-72, that is why before each experiment the fluid must be degassed by boiling. Secondly, during the experiment the fluid must be kept close the saturation temperature, which is 56 C for FC-72.

The strip heaters used in this experiment are manufactured by MINCO company. (HK5224R28 .9L 36A 9049). The heater dimensions are 125x11 mm. The heaters are in parallel connection and all three heaters are used at 2.2 A and 20 V during degassing and just one heater is used during the experiment at 0.6 A and 20 V. For that reason two of the heaters are connected to the power supply with toggle switches. (Figure 6) The heater stays on during the experiment is the one, which causes the least disturbance in the platinum wire area.

c. The Board and Adjustable Spring Assembly (Figure 7)

The 0.05 mm diameter platinum wire and the spring, which keeps the wire in tension against thermal expansion, are mounted on opposite sides of a Plexiglas board. As can be seen from Figure 7, by the adjustable spring assembly, it is possible to solder the platinum wire to the brackets under no tension and then apply required spring displacement gradually without breaking the wire by the adjustable spring assembly.

2. Front Chamber (Figure 3)

The front chamber is added to the main chamber to absorb the irregularities of the fluid displacement, which are caused by the piston motion and transmitted to the flow in the main chamber. For this purpose a spongy and permeable substance is placed in the opening between the two chambers as a flow dampener.

3. DC Motor and Piston Assembly (Figures 1 and 2)

In this experiment, a piston assembly has been designed to create a sinusoidal motion in the fluid and therefore over the platinum wire, to remove the bubbles forming on the wire. Under these circumstances, it is expected that the new bubbles will form on the surface and they will be removed by the next wave of the sinusoidal motion. This should lead to nucleate boiling with less temperature overshoot from the saturation point.

The frequency and the amplitude of the sinusoidal motion, which provide lower temperature overshoot from the saturation point, are to be determined. Because of this the variable piston stroke and frequency are needed, to investigate the possible frequency and amplitude ranges.

The variable frequency is achieved by a 27 volt, 1 amp DC motor. The rotational speed is measured by a micro switch tachometer. The variable stroke is achieved by a slot (Figure 1) on the rotating disk connected to the DC motor and its fixing mechanism. The piston has a 0.3762 in. diameter and runs through a replaceable Plexiglas part connected to the front chamber with four screws. In case, the amount of displacement with maximum piston stroke does not suffice to get satisfactory results and larger displacements are required, it is possible to replace this Plexiglas piece with an appropriate size piston.

B. INSTRUMENTATION (Figure 8)

The main goal of this experiment is to observe the boiling curve of FC-72 by obtaining the surface temperature of the platinum wire at various surface heat flux values. For that reason a platinum wire is calibrated to temperature vs. resistance values and heated electrically. The platinum wire is connected to a precision resistor in series. By this setup every time the voltage drop across the precision resistor is known, the current in the

line can be calculated by a simple division. Next the voltage drop across the platinum wire is measured and the resistance of the wire is calculated by dividing the voltage drop by the current. With the known resistance value, the surface temperature of the platinum wire can obtained from the calibration curve. Since the voltage drop and the current are measured, their product yields the heat transfer rate and division of the heat transfer rate by the surface area of the platinum wire gives the surface heat flux.

The bulk temperature of the fluid and the condenser temperature are measured by the data acquisition system. Some additional instrumentation is required to obtain the frequency of the DC motor and the piston. Figure 6 is the wiring diagram of power supplies and data acquisition system without thermocouples.

1. Platinum Wire

The platinum wire is a product of Goodfellow Advance Materials. It has 99.9% purity and 0.05 mm diameter. The length of the platinum wire in this experiment is 4.011 in. The Scanning Electron Microscope investigation of the sample wire from the same spool of the wire used in the experiment yielded 55μm diameter. The result of the platinum wire calibration is a linear temperature vs. resistance relationship. Moving from calibration bath to the experiment apparatus and especially inserting the board into the main chamber, requires very careful handling of such thin wire.

The resistance of the precision resistor, which is in series with the platinum wire, is 2Ω ± 1%. The precision resistor are manufactured by Dale company and have 25 watt power rating.

2. Power Supplies

In this set of experiments, four DC power supplies are used for the platinum wire and precision resistor in series, thermo-electric coolers in parallel, heaters in parallel and DC motor. These are:

HP 6289A DC Power Supply 0-40 V, 0-1.5 A with HP 59501B Isolated DAC/ Power Supply Programmer.(HP 6289A provided voltage to the platinum

wire and precision resistor and the voltage value is controlled by HP 59501B and the computer program.)

HP 6286A DC Power Supply 0-20 V, 0-10 A (to power the thermo-electric coolers.)

HP 6269B DC Power Supply 0-40 V, 0-50 A (to power heaters.)

HP 6289A DC Power Supply 0-40 V, 0-1.5 A (to power DC motor.)

3. Data Acquisition Unit and Communication Board

All the temperature and voltage measurements are done by HP 3497A Data Acquisition system via Unitek desktop computer with Pentium processor. An interface adapter provides communications between the computer and the acquisition system. The interface adapter is a National Instruments, GPIB-PCII/IIA with NI-488.2 software for DOS and Windows (part # 776092-01). The same interface adapter also allows the implementation of HP 59501B Power Supply Programmer.

The cards, which are used for temperature and voltage readings for data acquisition system, are as follows;

1. Thermocouple card	44422A 20 channel T-couple Acquisition.
2. Voltage card	44421A 20 channel Guarded Acquisition.

4. Frequency Measurements

Since the frequency of DC motor is very low, DC motor period is measured by 5001 Universal Counter-Timer and the frequency is obtained from period.

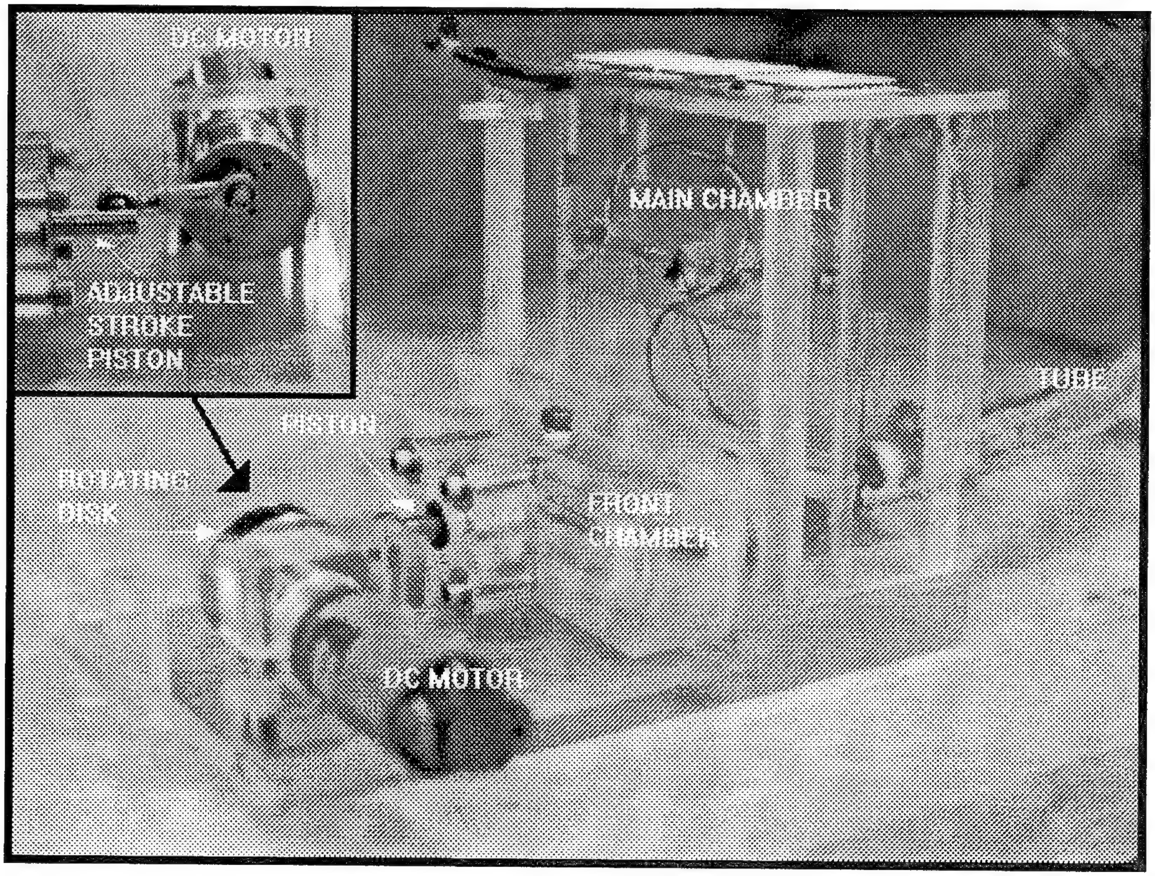

Figure 1. Isometric View of Experimental Apparatus

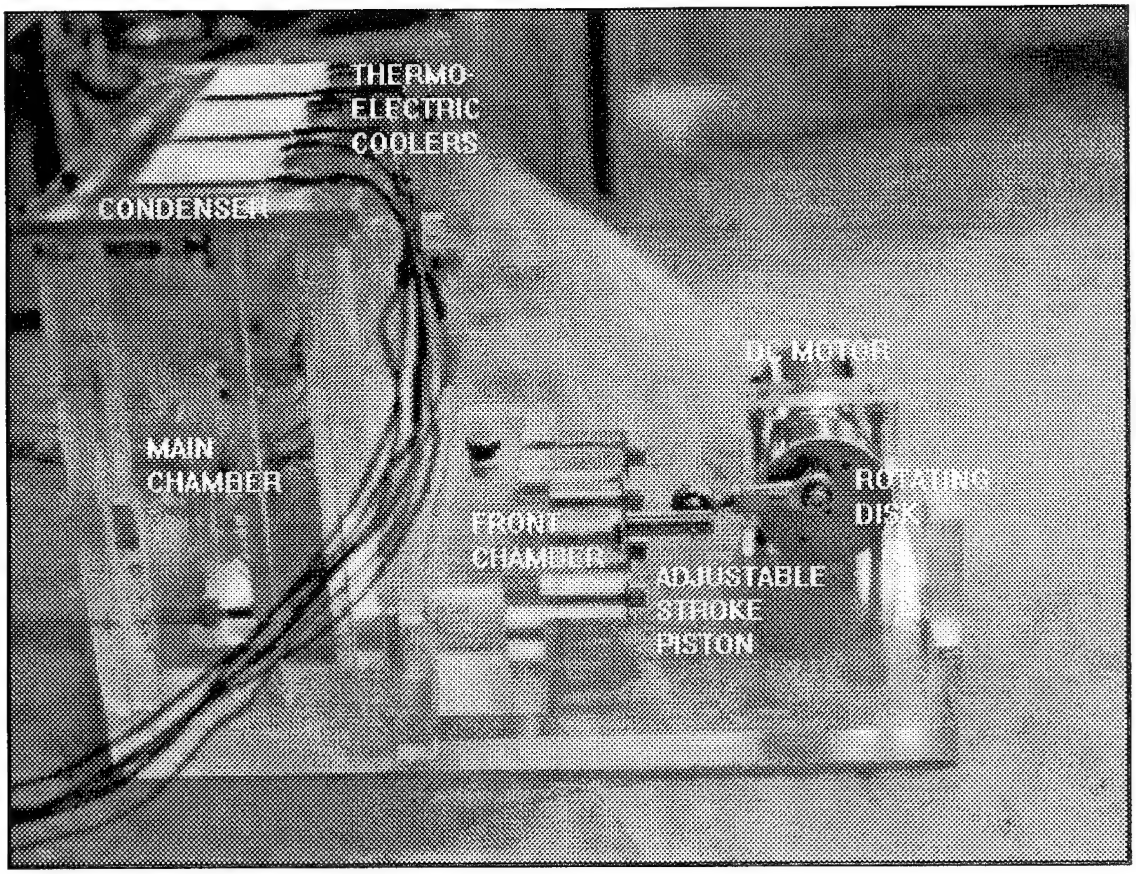

Figure 2a. Main Parts of Experimental Setup

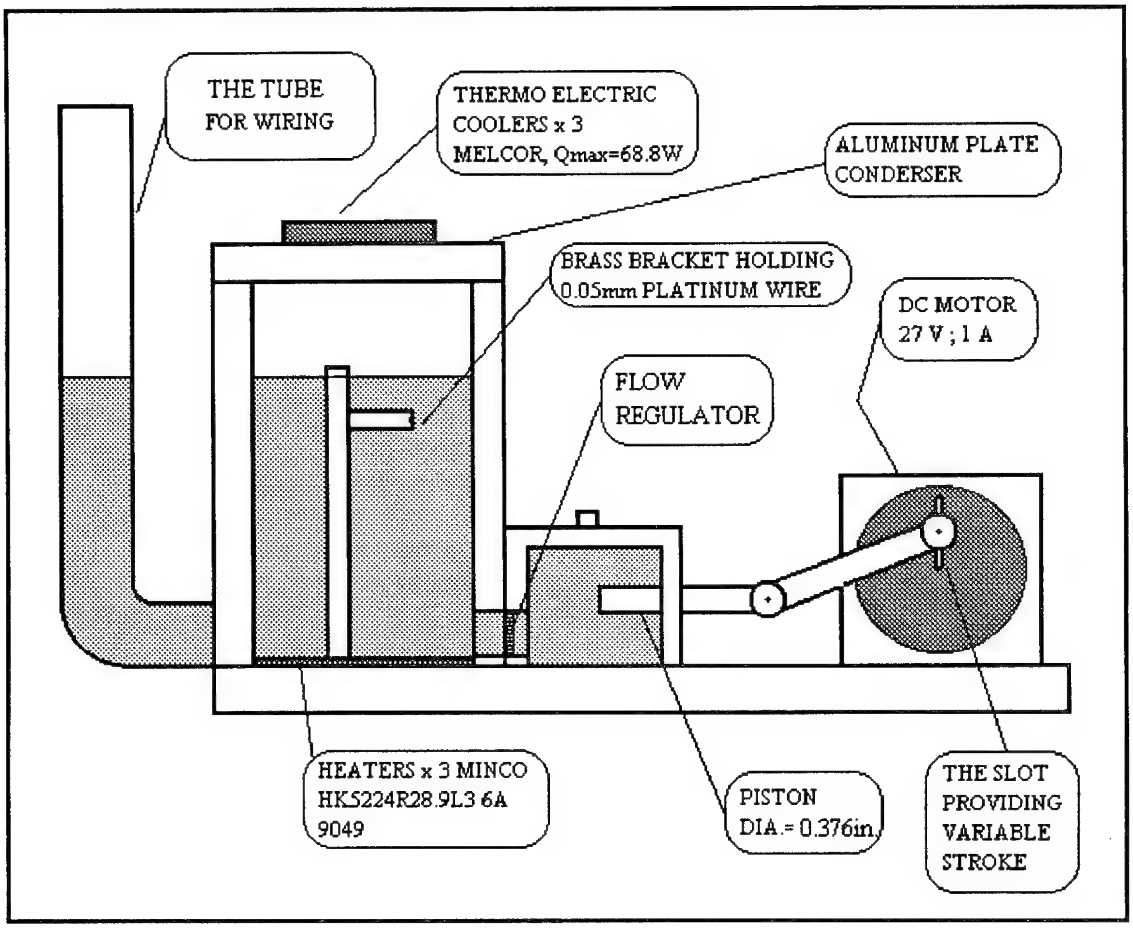

Figure 2b. Main Parts of Experimental Setup

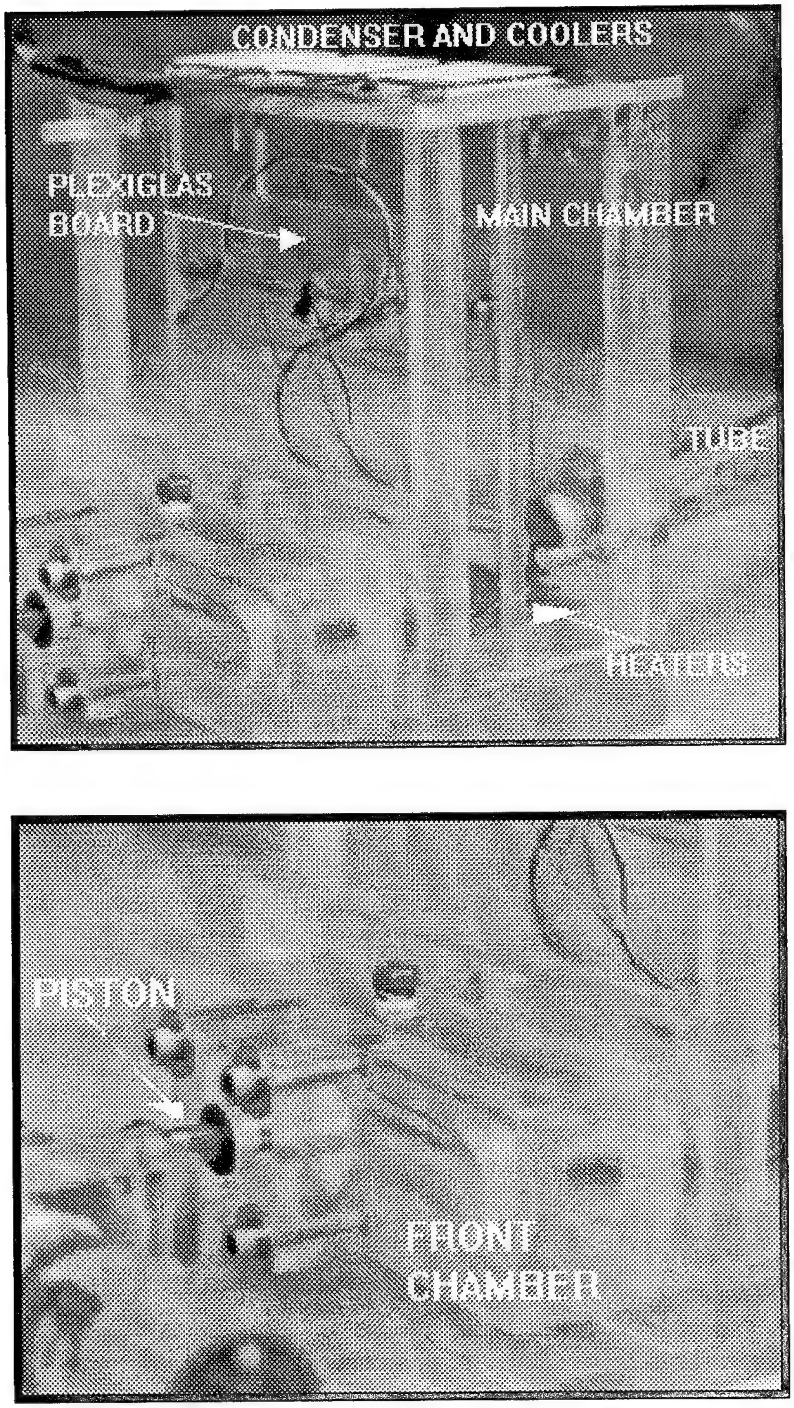

Figure 3. Main Chamber and Front Chamber

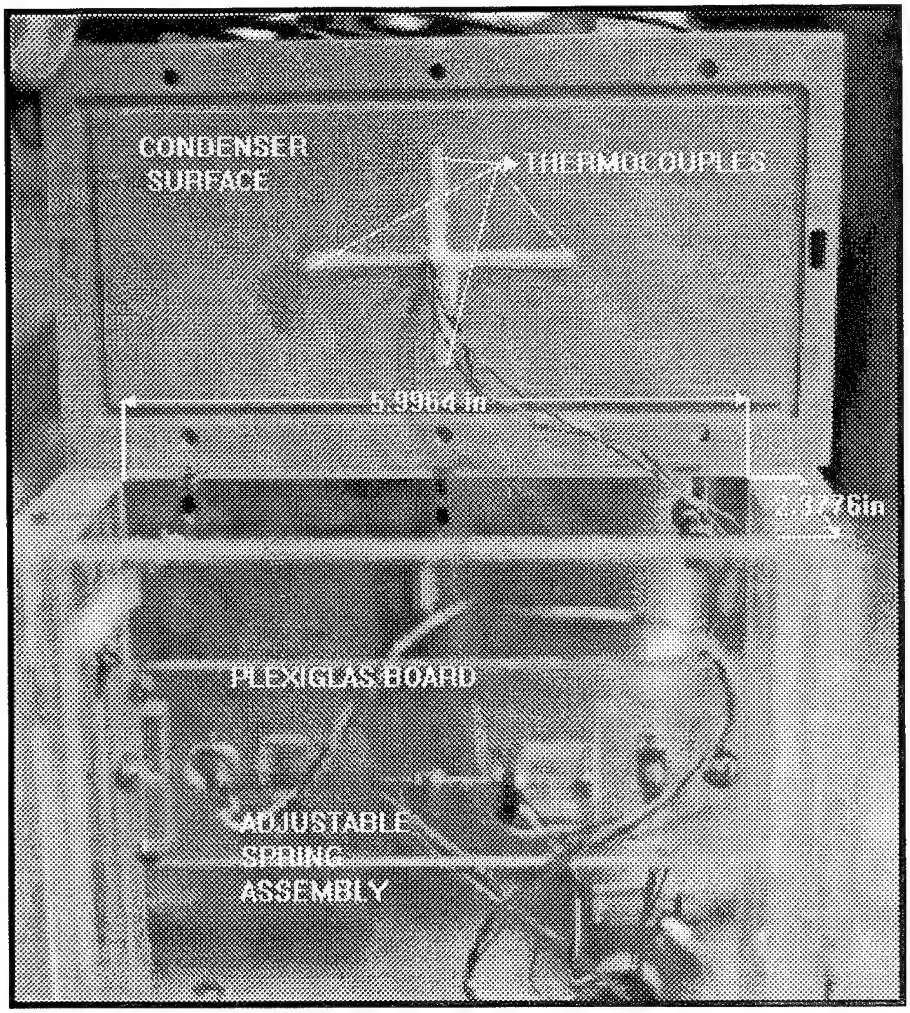

Figure 4a. Condenser and thermocouples

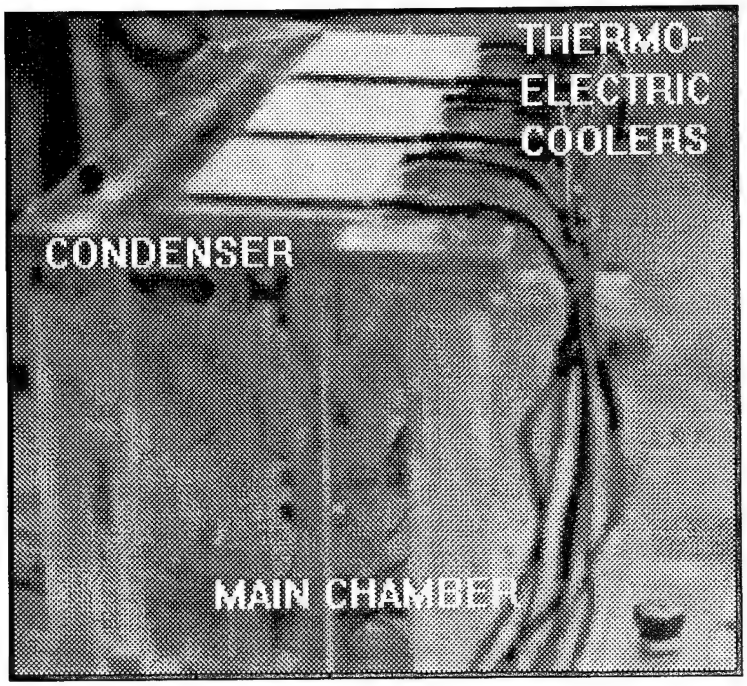

Figure 4b. Condenser and Coolers

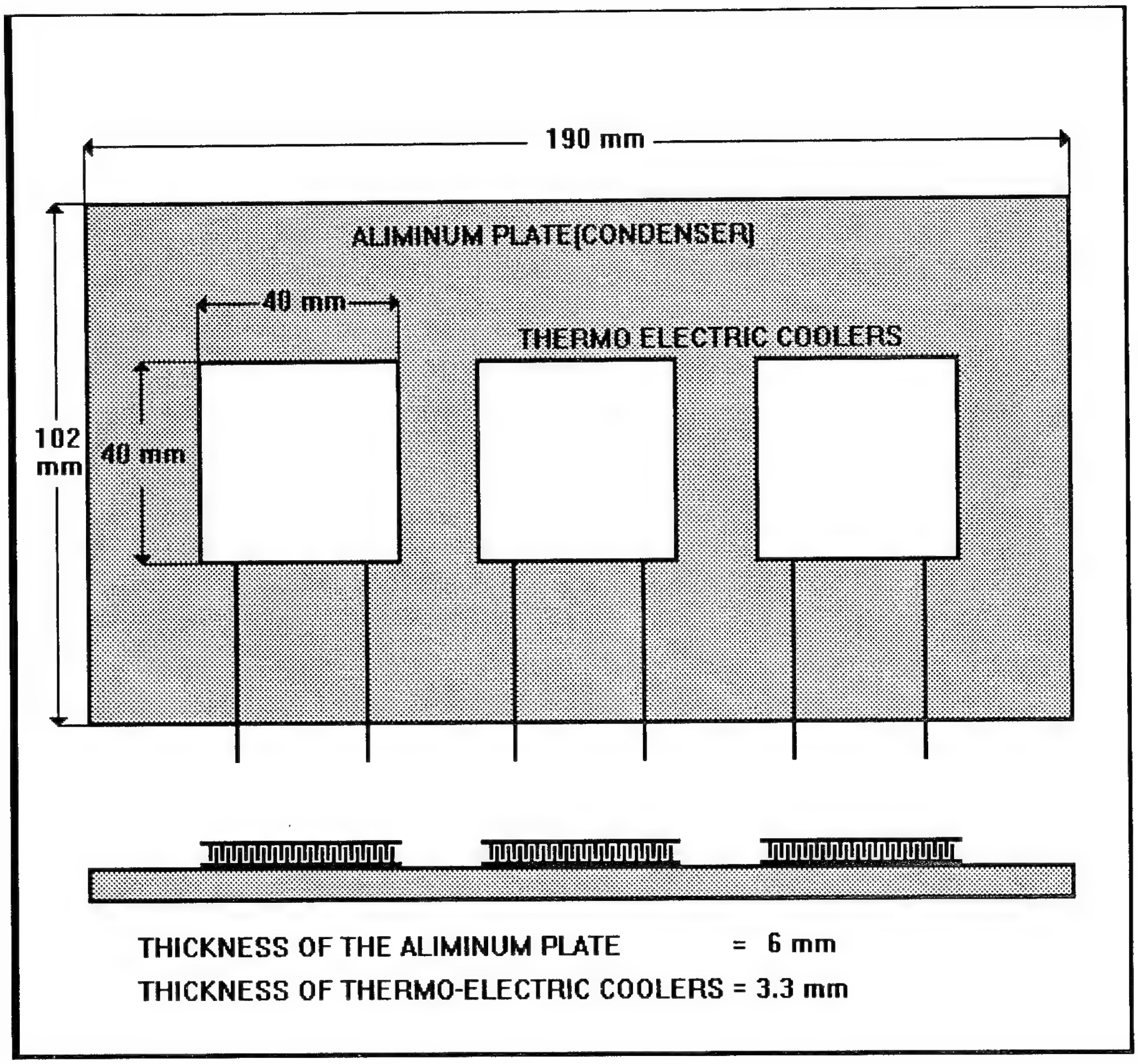

Figure 5. Schematic View of Condenser and Coolers

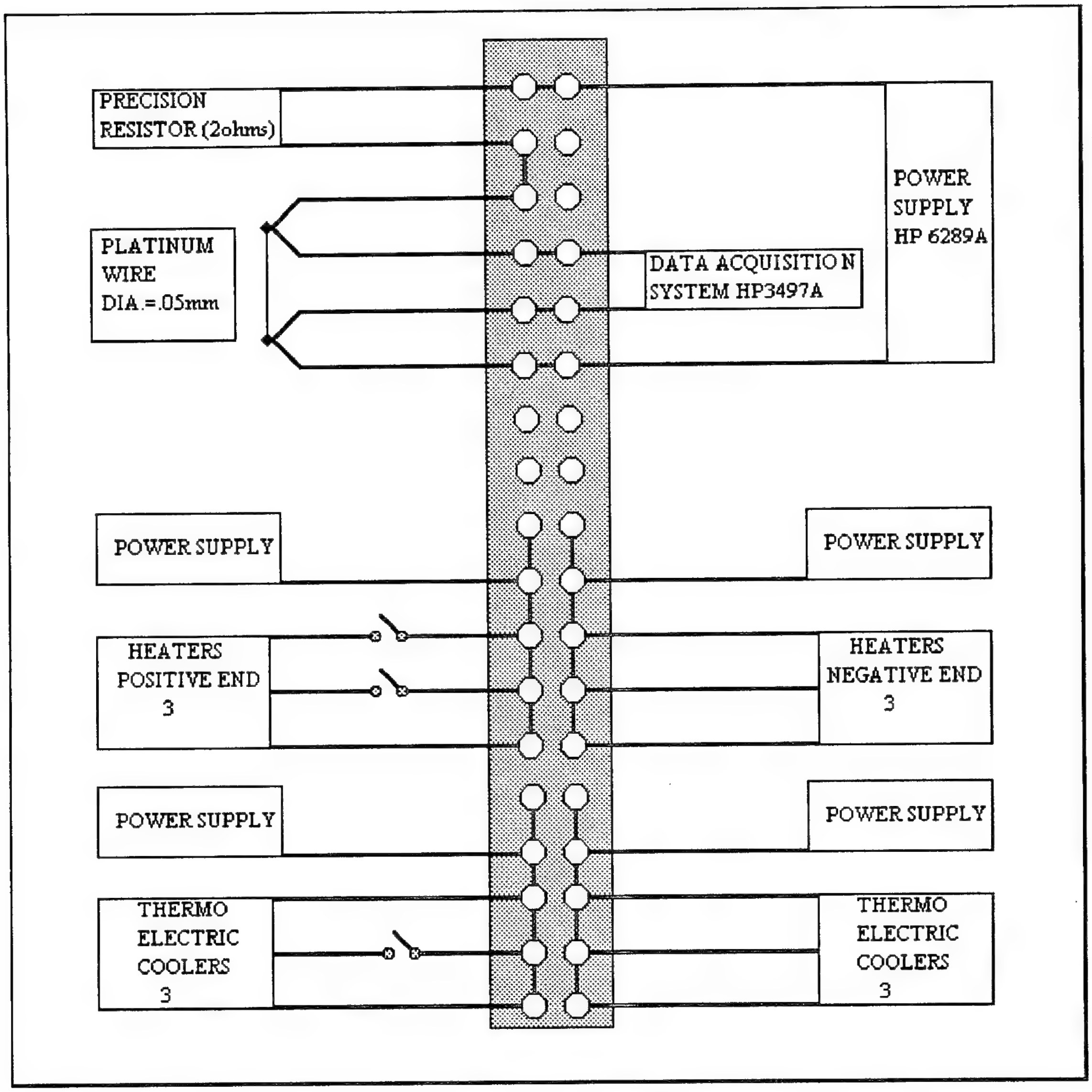

Figure 6. Data Acquistion Connections and Wiring Diagram of Power Supplies

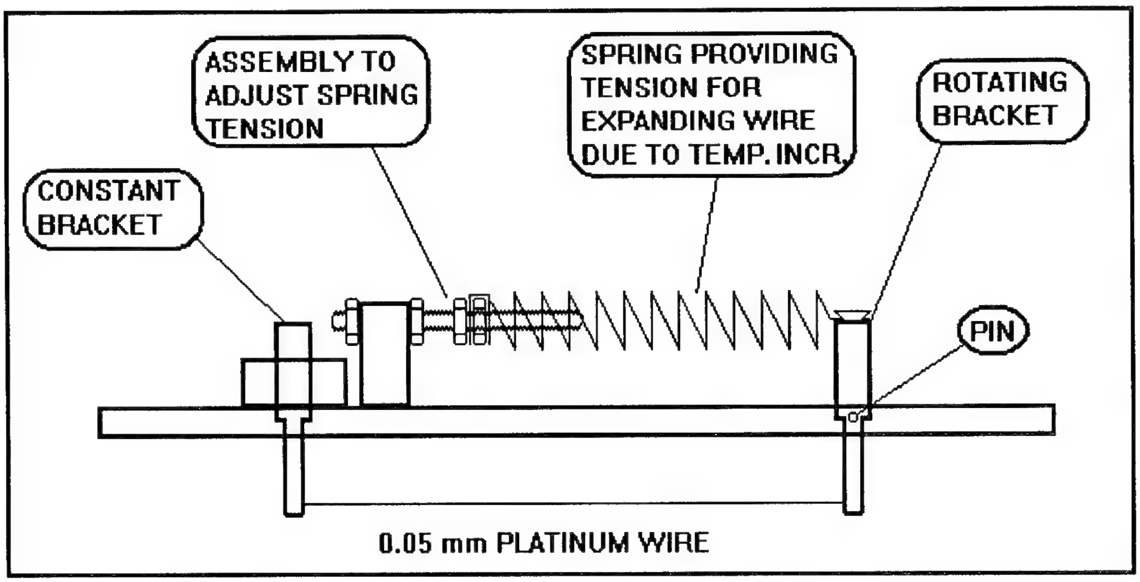

Figure 7. Platinum Wire and Spring Assembly

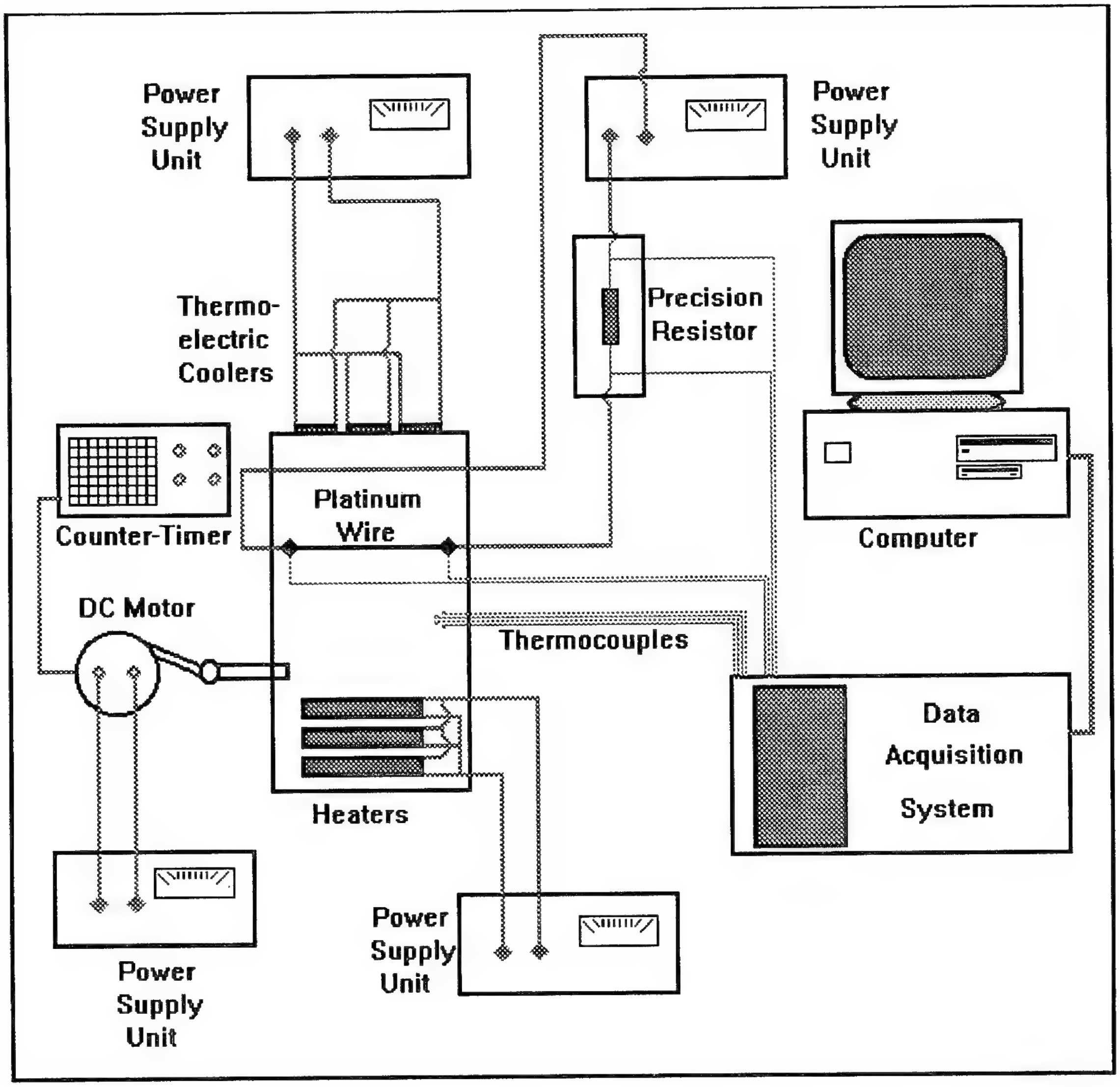

Figure 8. Schematic Drawing of the Experimental Setup

III. EXPERIMENTAL PROCEDURE

A. SYSTEM PREPARATIONS

Prior to each experimental run, the following preparation steps must be completed.

1. Check the fluid level in the main chamber and the tube. The level, in the main chamber, must be above the platinum wire, but should not exceed the top of Plexiglas board, which holds the platinum wire and the spring mechanism. The level, in the tube must be even with the level in the main chamber.

2. Adjust appropriate piston stroke length before experiment.

3. Turn on the HP 3497A Data Acquisition System. Warm up time for HP 3497A Data Acquisition System is approximately 1 hour.[Ref. 11 pp. 648]

4. The chambers must be insulated during degassing and experiment.

B. DEGASSING

Once system preparations are completed, the following steps are followed to accomplish degassing of FC-72, which is necessary to start an experimental run:

1. Power all three bulk heaters using the HP 6269B DC Power Supply at 20 V and 2.2 A. Be sure that the top two toggle switches, which are on the connection board, are on.

2. Power all three thermo-electric coolers using the HP 6286A DC Power Supply at 4.5 V and 5 A. Be sure that the third toggle switch on the connection board, which controls the middle thermo-electric cooler, is on.

3. Make it sure that the tops of thermo-electric coolers are covered by the aluminum finned heat sink.

4. Plug in the fan to 110 V electric source and blow air for aluminum finned heat sink.

Watch the fluid temperature increase and the condenser temperature decrease. Eventually the condenser temperature must be about 20 C and fluid temperature should go

up to saturation. At this temperature degassing takes place with boiling. The completion of degassing procedure takes 1.5 to 2 hours.

C. EXPERIMENTAL PROCEDURE

The following steps are followed before experiment:

1. Turn off two of the bulk heaters.

2. Decrease the power of remaining heater to 16 V and 0.6 A. Wait till the temperature drops down to a thermal equilibrium point.

3. Check piston stroke length.

4. Turn on 5001 Universal Counter-Timer.

5. Power DC motor by turning on HP 6289A DC Power Supply and adjust desirable frequency by DC motor voltage. Observe the period on the Universal Counter-Timer display. Stop motor after this adjustment.

6. Turn on HP 6289A DC Power Supply to power platinum wire and the precision resistor.

7. Turn on the computer and activate the interface adapter by answering Y to this question: DEVICEHIGH=/L:1,51680 = C: \GPIB-PC\GPIB.COM[Y,N]?

8. Run QBASIC, and load program EXPER3.BAS.

9. Enter file names to store temperature and heat flux values.

10. Run first four power settings without running the motor.

11. At the end of. fourth power setting, turn on HP 6289A DC Power Supply to run DC motor.

D. DATA ACQUISITION PROGRAM

Data acquisition is accomplished using a QBASIC program called EXPER3.BAS.

1. The data acquisition program executes these operations:

Sets up communications with HP 3497A and HP 6289A.

Controls power settings incrementally by the help of HP 59501B Power Supply Programmer.

Keeps time intervals between steps.

Reads thermocouple voltages and converts them to temperature values.

Calculates platinum wire temperature and heat flux.

Stores temperature and heat flux values in two separate data files.

2. For each power setting these measurements have been taken 10 times;

Bulk temperature (four thermocouples).

Condenser temperature (four thermocouples).

Ambient temperature (one thermocouple).

Platinum wire voltage drop.

Precision resistor voltage drop.

3. The first five steps of power settings, the voltage increment is 0.4 V. After sixth step, the increment reduces down to 0.2 V. At the end of 18th reading, the program starts decreasing the voltage with -0.2 V till step 30 and then the decrement becomes -0.4 V at every step.

4. Repeat the same steps for an other piston stroke and frequency configuration.

E. DATA REDUCTION

The following calculations are used to reduce the raw data obtained by experiments.

1. Condenser temperature;

$$T_{cond}(^{\circ}C) = \frac{(T_0 + T_1 + T_2 + T_3)}{4}$$

T_0 thru T_3 are thermocouple temperatures.

2. Fluid bulk temperature;

$$T_{bulk}(^{\circ}C) = \frac{(T_4 + T_5 + T_6 + T_7)}{4}$$

T_4 thru T_7 are thermocouple temperatures.

3. Current of platinum wire and precision resistor;

$$I_{Pt.Wire}(A) = I_{2\Omega} = \frac{V_{2\Omega}}{R_{2\Omega}}$$

where $R_{2\Omega} = 2\Omega$. (Precision Resistor)

4. Platinum wire resistance value;

$$R_{Pt.Wire}(\Omega) = \frac{V_{Pt.Wire}}{I_{Pt.Wire}}$$

5. Platinum wire surface temperature;

$$T_{surf}(^\circ C) = \varepsilon \cdot R_{Pt.Wire} + T_{y=0}$$

where;

ε = 50.4159 (slope of calibration curve)

$T_{y=0}$ = -252.3321 (y axis intercept of calibration curve)

6. Fluid film temperature;

$$T_{film}(^\circ C) = \frac{T_{surf} + T_{bulk}}{2.0}$$

7. Heat flux from platinum wire;

$$q(W/m^2) = \frac{I_{Pt.Wire} \cdot V_{Pt.Wire}}{A_{Pt.Wire}}$$

where $A_{Pt.Wire}(m^2) = \pi \cdot L_{Pt.Wire} \cdot D_{Pt.Wire}$

8. Piston displacement;

$$\Delta_{Piston}(mm^3) = \frac{\pi}{4} \cdot D^2_{Piston} \cdot L_{Stroke}$$

9. Amplitude of oscillation in the main chamber;

$$A_{Amplitude}(mm) = \frac{\Delta_{Piston}}{a \cdot b}$$

where a and b inner length and width of the main chamber respectively.

10. Frequency calculation;

$$f(Hz) = \frac{1}{T_{Period}(s)}$$

To evaluate the experiments, the data plotted heat flux vs. surface temperature by three MATLAB codes in Appendix D, Section B. Data processing has two parts; First the average of ten readings for each step is calculated. Second the natural convection part numerically calculated with recommended correlation by Kuehn and Goldstein [Ref. 12] for natural convection around small horizontal cylinders. Then both results are plotted. For fluid properties, Egger's results [Ref. 13] are used.

IV. RESULTS AND DISCUSSION

In this experimental study, the boiling curve of FC-72 is determined in non-oscillating bulk fluid. Then the changes in the boiling curve of FC-72 is observed when the bulk fluid is oscillating at different amplitudes and frequencies. All experiments are done at atmospheric pressure and the same platinum wire of 0.055 mm diameter is used.

The results of these experiments are presented in the plots of heat flux vs. the difference of platinum wire temperature and saturation temperature in Figures 9 through 14b. Some of the experiments are conducted for repeatability. The results of the experiments, which are conducted under the same conditions are in agreement within the uncertainty limits.

Figure 9 is the boiling curve of FC-72 without any oscillation in the bulk fluid. The hysteresis between the increasing and the decreasing heat flux shows the amount of superheat necessary for the onset of nucleate boiling. As soon as the boiling starts the wire temperature decreases abruptly. Figure 10 is the boiling curve of FC-72 with the oscillation amplitude of 0.117 mm and oscillation frequency of 0.69 Hz. The decrease in the hysteresis is obvious compared to Figure 9.

A. BOILING CURVES OF FC-72 (BOILING WITHOUT OSCILLATION)

In order to see the effects of oscillation on the boiling regimes of FC-72, it is necessary to observe the boiling under non-oscillating conditions, then it is possible to compare the results with the oscillating cases. Figure 11 shows the results of Experiments 4, 18 and 14, which are conducted without any oscillation. In the following discussion, the boiling regimes of these experiments will be compared.

1. Natural Convection (Figures 9 and 11)

In Experiments 4, 18 and 14. the natural convection part of the experiments occurs between the heat flux values of 18,700 and 86,300 W/m^2. After 86,300 W/m^2 is exceeded, nucleate boiling starts. At this heat flux value the platinum wire temperature is 99.7 C, and the difference between the platinum wire temperature and the saturation temperature

$(T_{Wire} - T_{sat})$ is 43.7 C. This is the highest temperature overshoot observed during this set of experiments. In these experiments, the bulk temperature changes between 49 and 54.5 C (Table 1a) in the natural convection phase. The bulk temperature has almost no effect on the natural convection curve. This observation confirms Egger's result on the natural convection and the bulk temperature relation [Ref. 13 pp. 23]. The data acquired in this part of the experiments is in agreement with the correlation suggested by Kuehn and Goldstein [Ref. 12] for natural convection heat transfer around small diameter cylinders.

2. Nucleate Boiling

As soon as nucleate boiling starts, the temperature of the platinum wire drops. The drop in the wall temperature value changes from 11.8 to 12.6 C in different experiments (Table 1a). The platinum wire temperature just after the onset of boiling is 11.8% to 13.5% less than the maximum superheat temperature value.

Superheat point	Pt.Wire Temp. Drop (C)	ΔT (C)	Bulk Temp. (C)	Heat Flux (W/m^2)
EXP 4	99.6 to 87.8	11.8	54.5	86,300
EXP 18	99.7 to 87.1	12.6	52.1	86,300
EXP 14	99.7 to 87.3	12.4	49.0	86,300

Table 1a. The Comparison of Maximum Superheat Point in Three Non-Oscillating Experiments.

3. Critical Heat Flux (CHF) and Entry to Film Boiling

The location of the regime change from nucleate boiling to film boiling varies the most in different experiments. Different platinum wire temperatures and different critical heat fluxes are observed in the non-oscillating experiments for this particular point. This part of the boiling curve is affected most by the bulk temperature. It is observed that with the decreasing bulk temperature, CHF increases (Table 1a). In Experiment 14 (Figure 11

and Table 1a), when the bulk temperature is 48.4 C, CHF is 152,000 W/m², but in Experiment 18, the CHF of 132,000 W/m² occurs at the bulk temperature of 51.8 C. At that time the platinum wire temperatures for Experiments 14 and 18 are 89.5 and 89.2 C respectively.

CHF point	Pt.Wire Temp. (C)	Bulk Temp. (C)	Heat Flux (W/m²)
EXP 4	87.7	54.9	122,500
EXP 18	89.2	51.8	132,000
EXP 14	89.5	48.4	152,200

Table 1b. The Comparison of Critical Heat Flux in Three Non-Oscillating Experiments. CHF Increases with the Decreasing Bulk Temperature.

B. OSCILLATION EFFECTS ON BOILING CURVE

Three different piston strokes of 10, 15 and 20 mm, created three different oscillation amplitudes in the fluid surrounding the platinum wire. The amplitudes are 0.078, 0.117 and 0.156 mm respectively. At each oscillation amplitude five frequencies are tested. These frequencies are from lowest to highest: 0.4, 0.56, 0.69, 0.8 and 1.5 Hz.

1. Amplitude and Frequency Effects on the Boiling Curve

Tables 2a and 2b represent the maximum superheat temperature and CHF values of the boiling curve of the non-oscillating and oscillating FC-72. Figures 12a through 14b are the boiling curves of the non-oscillating and oscillating FC-72.

a. Amplitude of 0.078 mm

The boiling curve at this amplitude and five frequencies can be seen in Figures 12a and 12b. The wire temperature, bulk temperature and the heat flux values can be seen in Table 2a for the maximum superheat point and Table 2b for CHF point. The drop in the maximum temperature overshoot is 8.7% for frequency of 0.4 Hz and 19.0% for frequency of 1.5 Hz. The heat flux at this point changes from 71,700 to 72,000 W/m²

Critical heat flux decreases for three frequencies from 132,000 W/m² to 122,000 W/m². For the other two frequencies CHF remains unchanged as in non-oscillating FC-72.

Amplitude (mm)	0.078			0.117			0.156		
Frequency (Hz)	Wire Temp (C)	Bulk Temp (C)	Heat Flux (W/m²)	Wire Temp (C)	Bulk Temp (C)	Heat Flux (W/m²)	Wire Temp (C)	Bulk Temp (C)	Heat Flux (W/m²)
No Stroke	99.7	52.1	86,300	99.7	52.1	86,300	99.7	52.1	86,300
0.4	95.9	54.0	71,700	92.7	53.0	72,100	94.7	53.2	72,000
0.56	94.7	53.3	71,800	89.1	54.8	58,700	93.6	50.9	72,000
0.69	94.3	52.2	72,000	87.6	54.9	58,800	95.3	51.4	79,100
0.8	95.7	53.4	71,800	88.2	52.3	72,500	95.6	52.3	79,100
1.5	91.4	52.8	72,200	88.6	53.9	58,700	95.1	53.6	71,800

Table 2a. Superheat Values for Oscillating FC-72. For No Stroke Case the Results of Experiment 18 is Used.

b. Amplitude of 0.117 mm

The best results in the temperature overshoot and heat flux drops are achieved at this amplitude. Figures 13a and 13b reflects this decrease. At the frequency of 0.69 Hz, the overshoot decreases to its lowest magnitude. In the non-oscillating boiling case the maximum temperature overshoot value is 99.7 C, at this frequency, the maximum temperature overshoot is read as 87.6 C with 27.7% drop. The heat flux value at which the onset of nucleation boiling occurs, decreases up to 32.0% from 86,300 W/m² to 58,700 W/m².

The CHF value stays almost unchanged during the experiments at this amplitude.

c. Amplitude of 0.156 mm

Just like the amplitude of 0.078 mm, at this amplitude temperature overshoot and heat flux drops are achieved, but they are not as large as the amplitude of 0.117 mm. The results of this amplitude can be seen in Figures 14a and 14b.

The remarkable side of this set of experiments is CHF. As can be seen from Table 2b, CHF value goes up from 132,000 W/m² to 142,000 W/m² at the same wall temperature as the non-oscillating case.

Amplitude (mm)	0.078			0.117			0.156		
Frequency (Hz)	Wire Temp (C)	Bulk Temp (C)	Heat Flux (W/m²)	Wire Temp (C)	Bulk Temp (C)	Heat Flux (W/m²)	Wire Temp (C)	Bulk Temp (C)	Heat Flux (W/m²)
No Stroke	89.2	51.8	132,000	89.2	51.8	132,000	89.2	51.8	132,000
0.4	87.8	54.0	122,500	87.4	52.5	132,000	88.8	53.1	132,000
0.56	88.4	53.3	132,000	88.0	54.5	132,000	88.8	50.8	132,000
0.69	87.9	52.3	122,500	87.4	54.7	123,000	89.3	51.2	142,000
0.8	88.4	53.3	132,000	88.0	52.0	132,000	89.7	52.2	142,000
1.5	87.8	52.6	123,000	87.5	53.5	123,000	88.5	53.5	132,000

Table 2b. Critical Heat Flux Values for Oscillating FC-72. For No Stroke Case the Results of Experiment 18 is Used.

C. FURTHER DISCUSSIONS

A total of 46 experiments have been conducted to achieve the boiling curve of FC-72 at various bulk temperatures, oscillation frequencies and amplitudes. The effects of the oscillation amplitudes and frequencies on the superheat, which is necessary to initiate nucleate boiling, have been observed.

In Experiment 18 (Figure 9) without any oscillation in the bulk fluid, before the boiling starts the wall temperature goes up to 99.7 C and then as soon as the boiling starts the wire temperature drops 12.6 C. On the other hand in Experiment 39 (Figure 10) with the oscillation amplitude of 0.117 mm and oscillation frequency of 0.69 Hz the wall temperature goes up to only 87.6 C. This is the smallest temperature overshoot for nucleate boiling achieved in this study and it is 27.7% less than the no oscillation case temperature overshoot, which is Experiment 18.

Under all circumstances, the temperature overshoot value is reduced with oscillation from 8.7% (f = 0.4 Hz, A = 0.078 mm) to 27.7% (f = 0.69 Hz, A = 0.117 mm). The heat flux value for the onset of nucleate boiling drops in all frequencies and amplitudes. The drop is between 32.0% (f = 0.56 Hz, A = 0.078 mm) and 8.3% (f = 0.69 Hz, A = 0.156 mm).

Figure 15 shows the maximum temperature overshoot values required for boiling incipience in FC-72 at three different amplitudes and five different frequencies. As overall result at the oscillatory conditions, there is a certain decrease in required superheat.

The amplitude of 0.117 mm is less effective at low and high frequencies, but at 0.69 Hz the superheat reaches its lowest value.

The reduction of superheat for the onset of boiling can be attributed to the way the bubbles forming at the nucleation sites depart from the hot surface. When the bubble completes its growth in the cavity, it starts to grow bigger on the outer surface. At this point in highly wetting fluids like FC-72, the bubble can not depart the surface easily and this occurrence results in the superheat before the boiling incipience.

The bubble snapping process from the cavities is accelerated due to the oscillation. This helps to overcome the surface tension effects of highly wetting FC-72 dielectric fluid. As it is expected at some amplitudes like 0.117 mm, the oscillation is more effective to remove forming bubbles from the hot surface, but at the other two amplitudes the resultant reduction is not as high as 0.117 mm. This occurrence can be related to the active nucleation sites on the hot surface and the effective bubble size.

In The Following Figures from 9 to 14b These Symbols are Used to Clear the Plots:

x	Increasing Heat Flux (Wire Temp.-Saturation Temp)
o	Decreasing Heat Flux (Wire Temp.-Saturation Temp)
+	Increasing Heat Flux (Bulk Temperature)
.	Decreasing Heat Flux (Bulk Temperature)
-	Kuehn-Goldstein Correlation (Natural Convection)

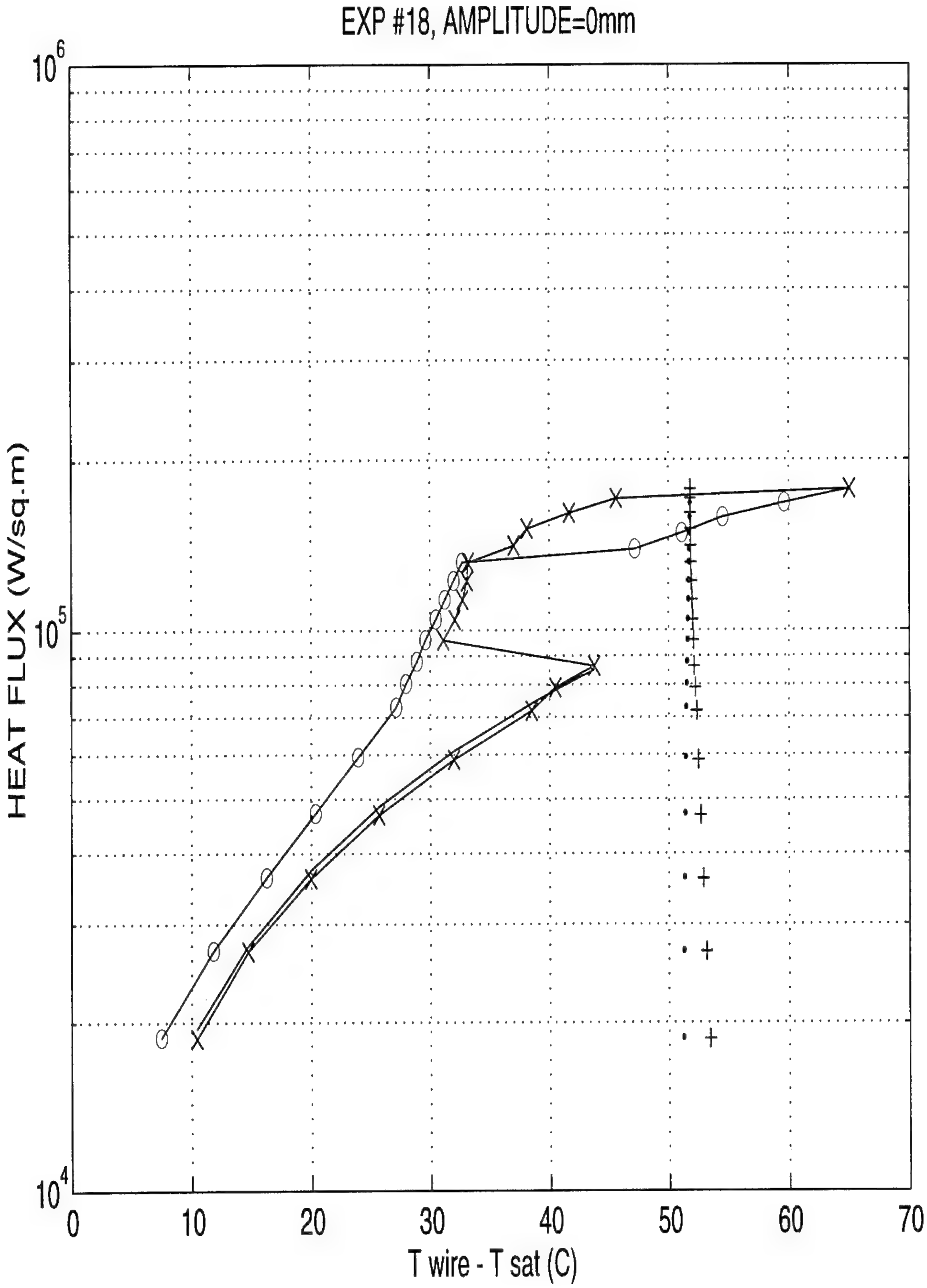

Figure 9. The Boiling Curve of FC-72 without oscillation.

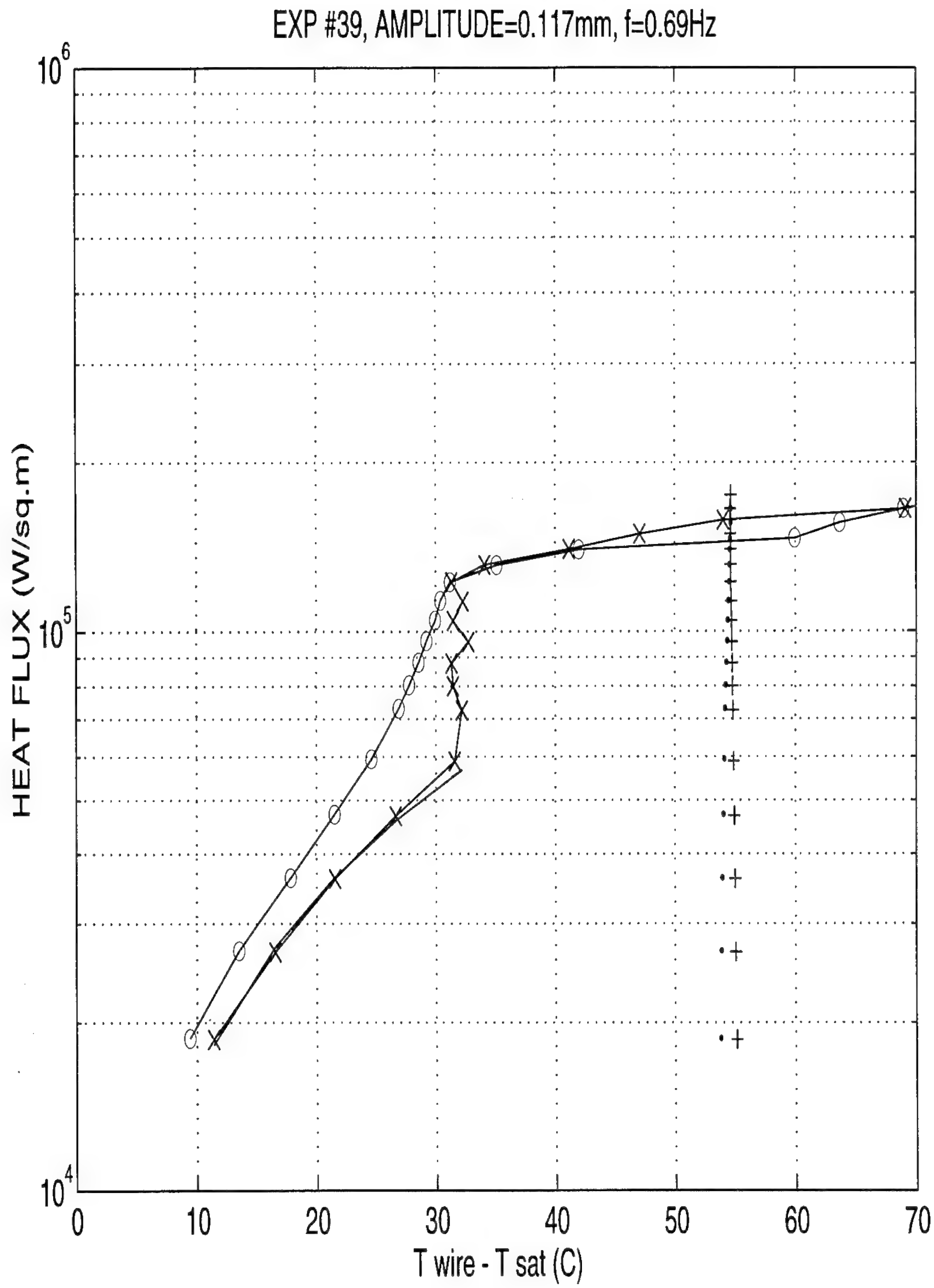

Figure 10. The Boiling Curve of FC-72 with the Lowest Temperature Overshoot.

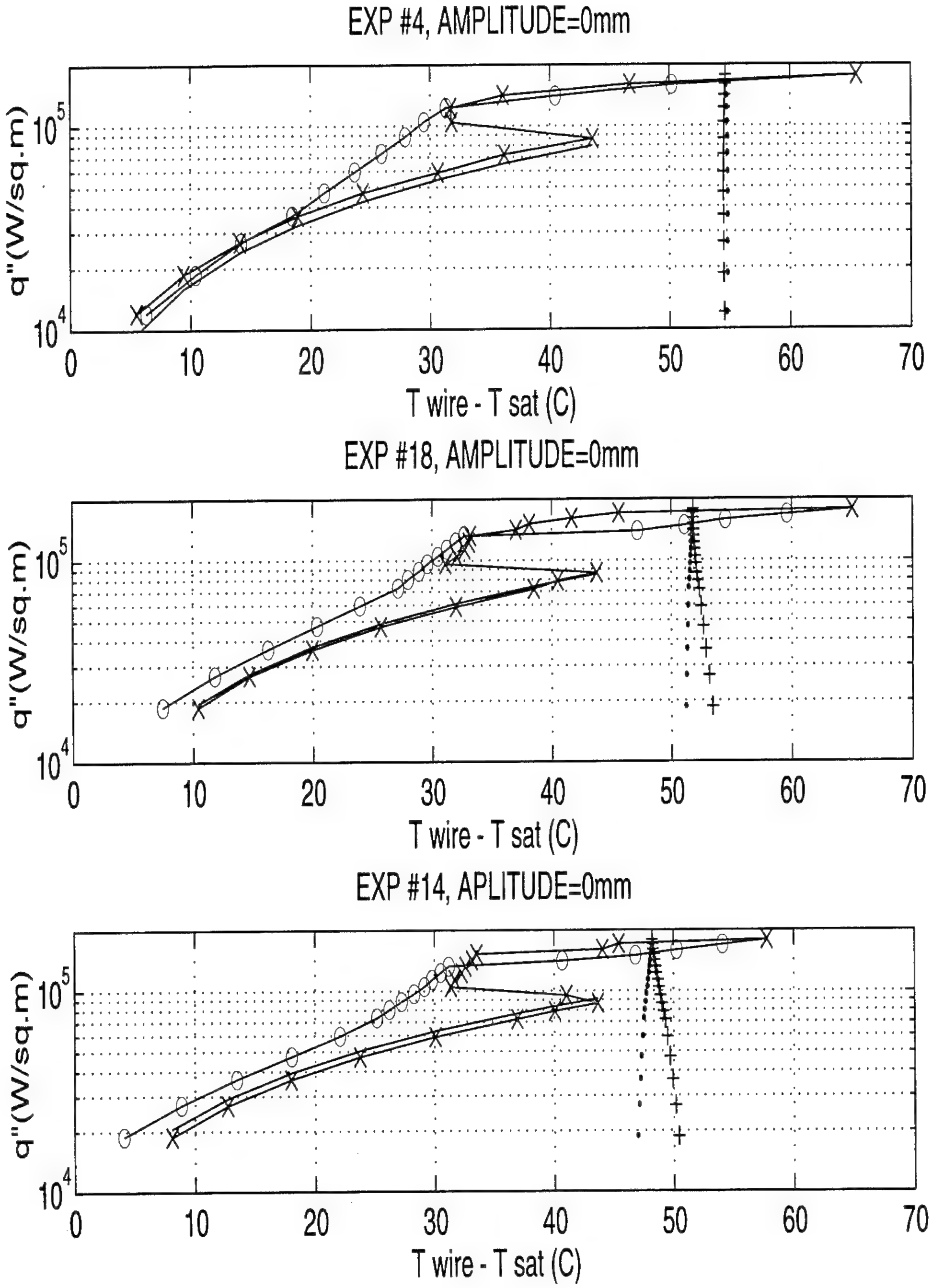

Figure 11. All Three Plots in Figure 11 are the Boiling Curves of FC-72.

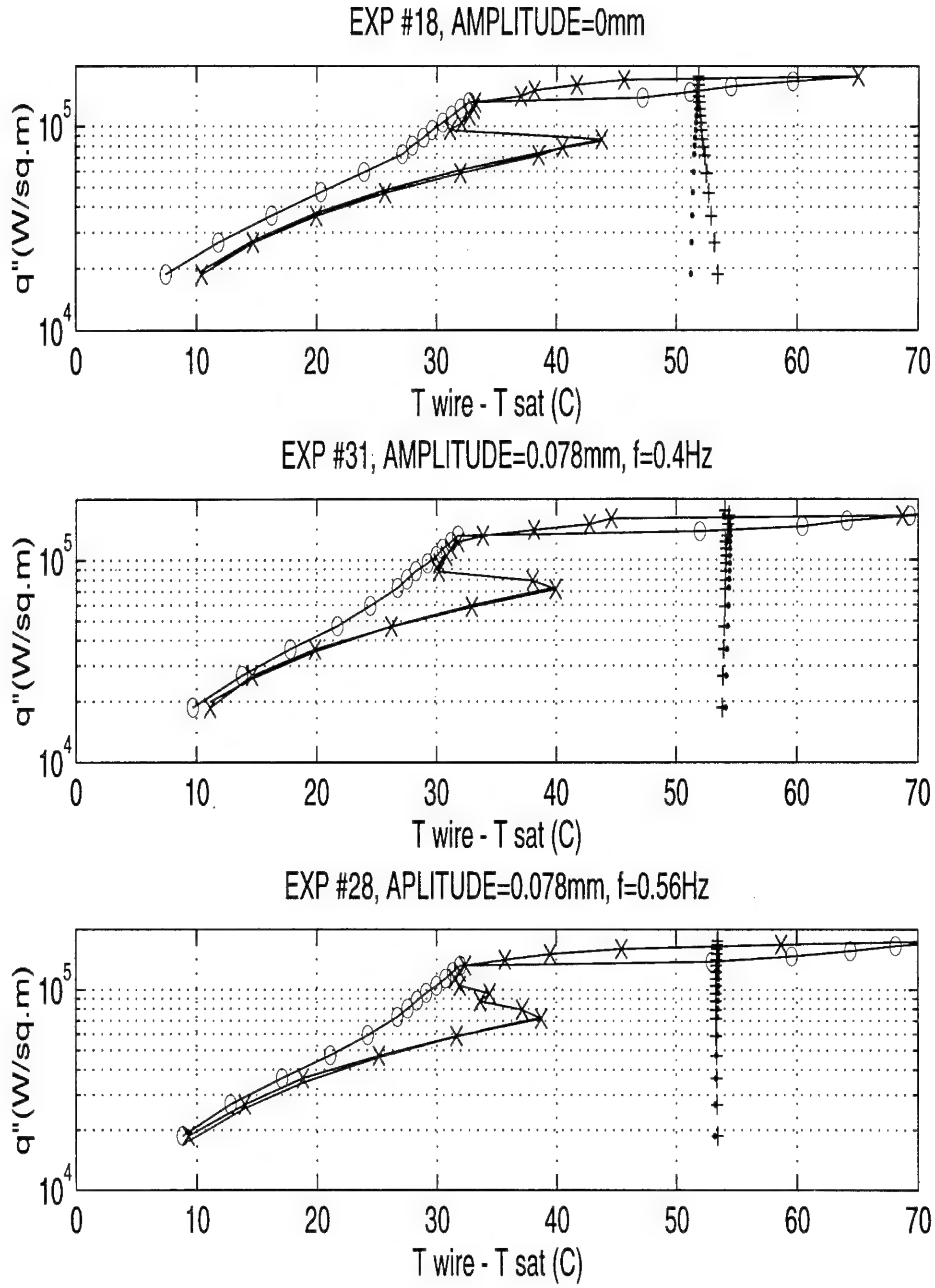

Figure 12a. Top Plot in Figure 12a is the Boiling Curve of FC-72. Other Five Plots in Figures 12a and 12b are the Boiling Curves with an Oscillation of Amplitude 0.078mm and Five Different Frequencies.

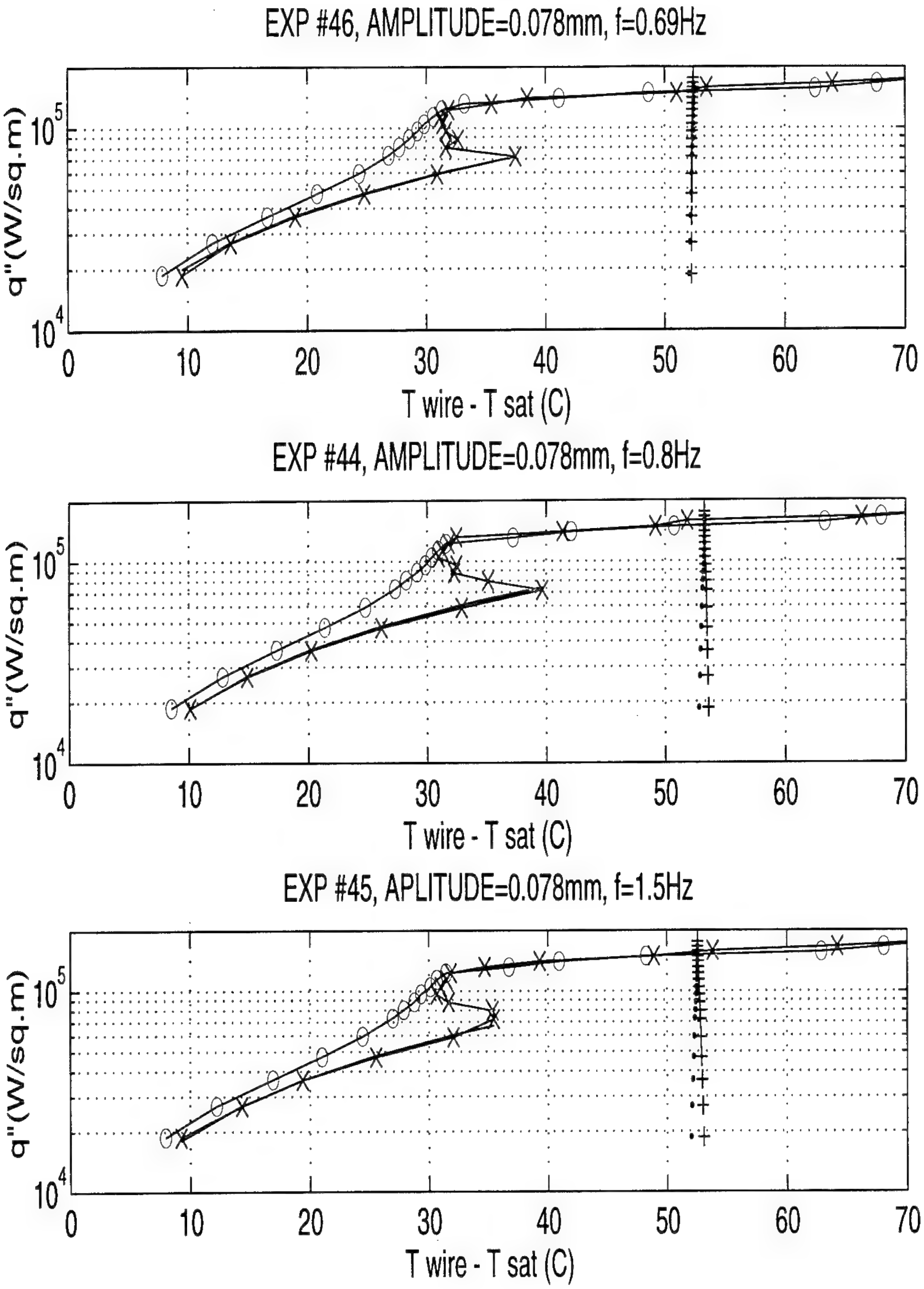

Figure 12b. Top Plot in Figure 12a is the Boiling Curve of FC-72. Other Five Plots in Figures 12a and 12b are the Boiling Curves with an Oscillation of Amplitude 0.078mm and Five Different Frequencies.

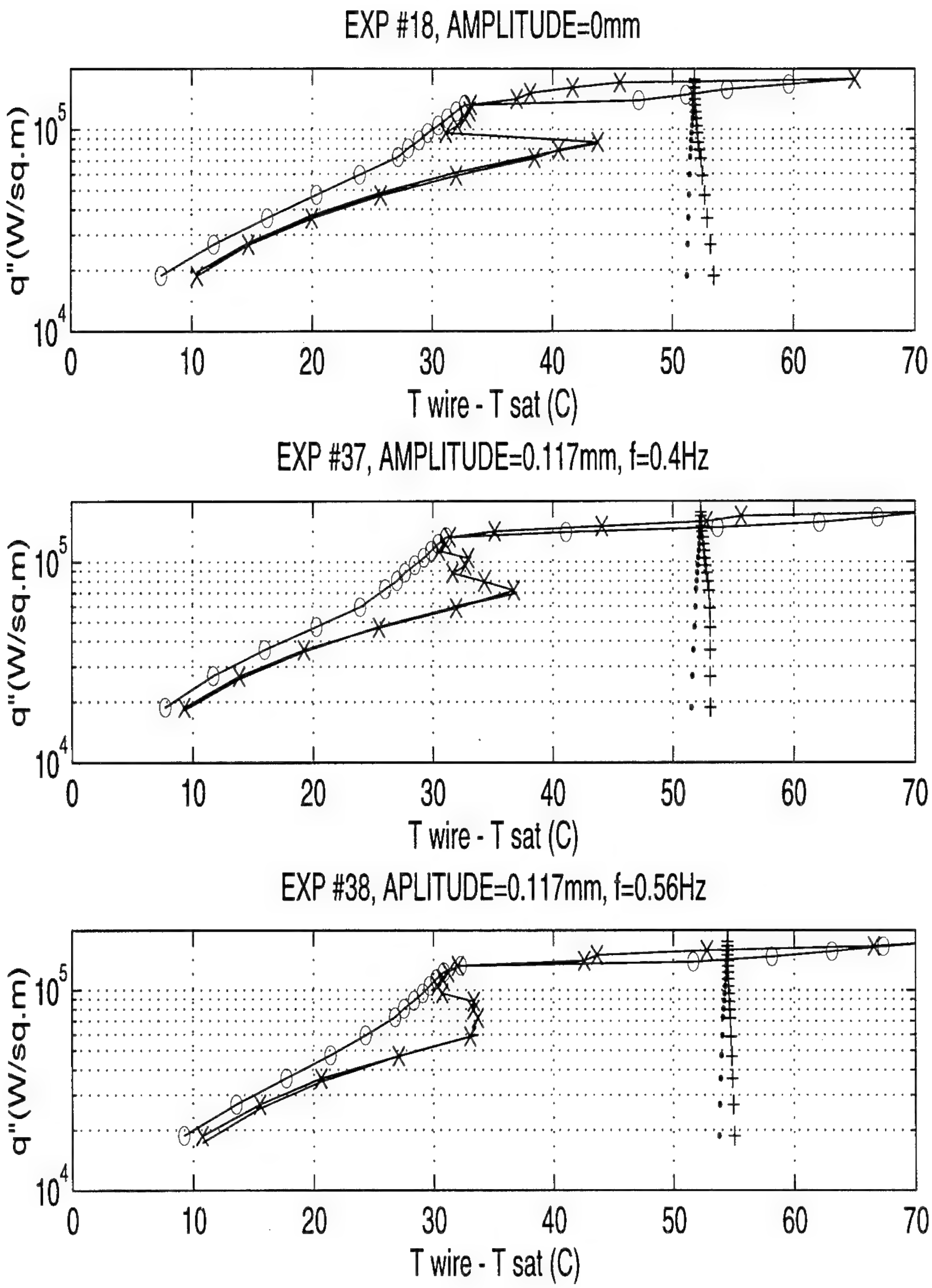

Figure 13a. Top Plot in Figure 13a is the Boiling Curve of FC-72. Other Five Plots in Figures 13a and 13b are the Boiling Curves with an Oscillation of Amplitude 0.117mm and Five Different Frequencies.

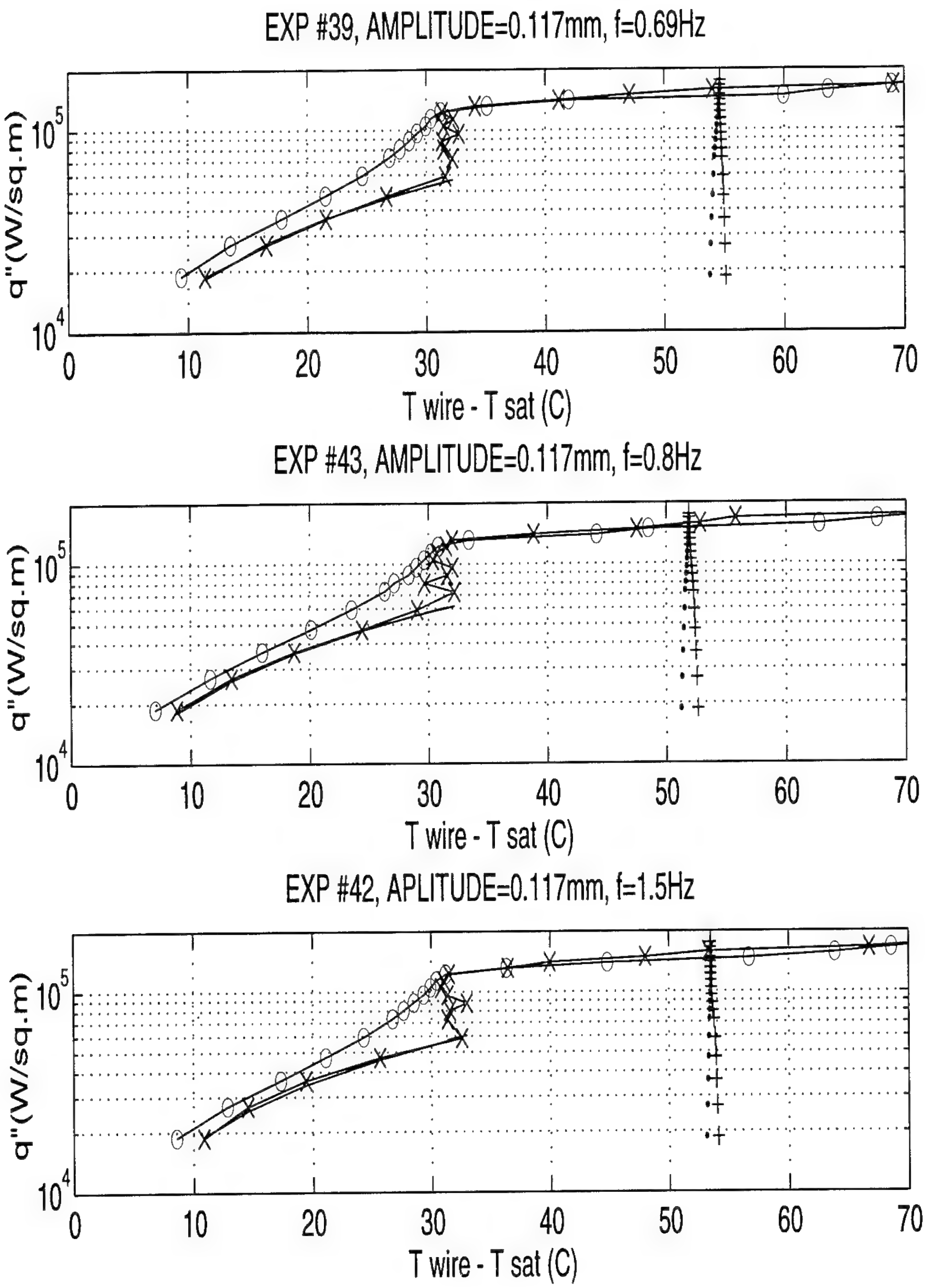

Figure 13b. Top Plot in Figure 13a is the Boiling Curve of FC-72. Other Five Plots in Figures 13a and 13b are the Boiling Curves with an Oscillation of Amplitude 0.117mm and Five Different Frequencies.

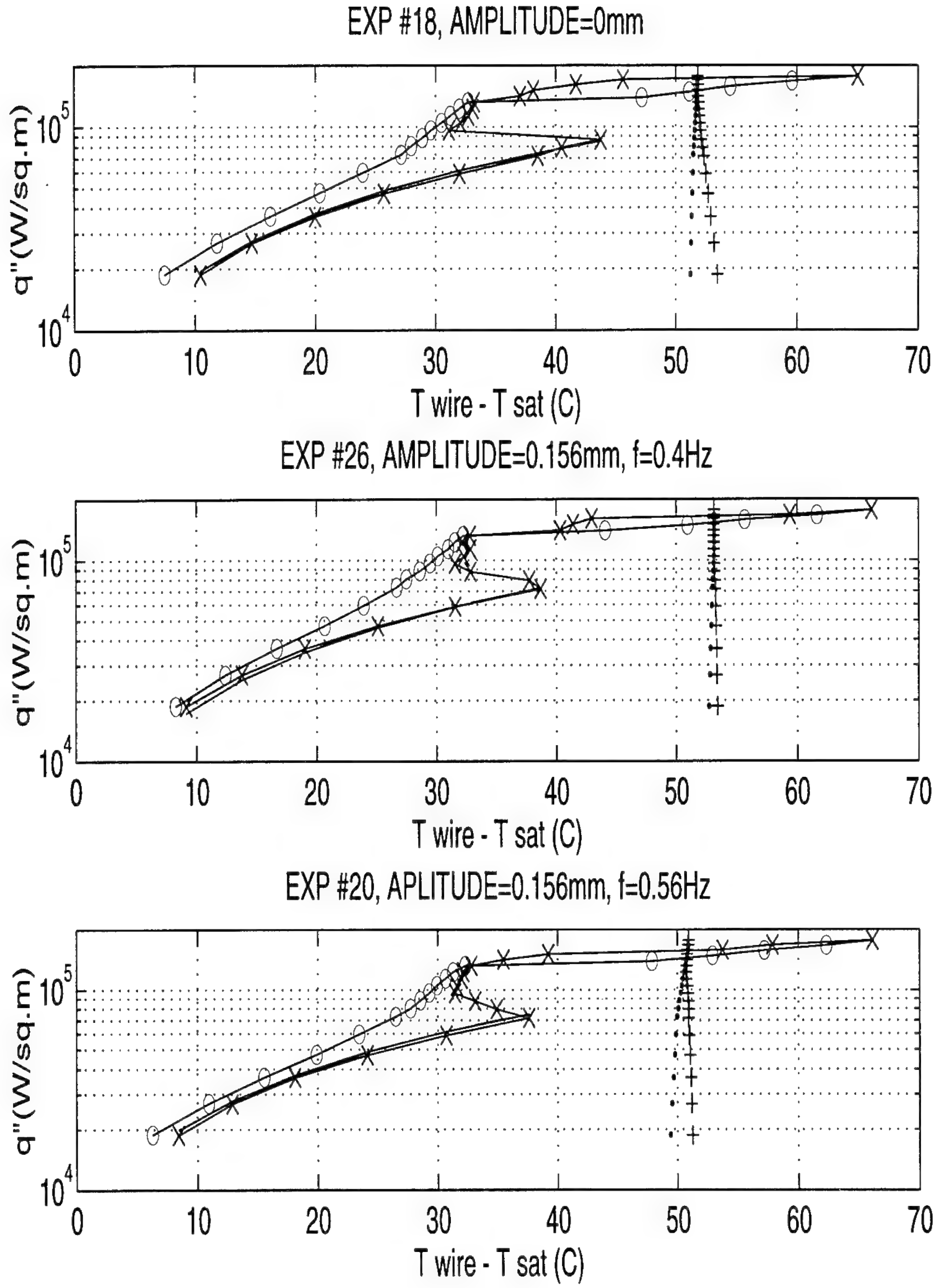

Figure 14a. Top Plot in Figure 14a is the Boiling Curve of FC-72. Other Five Plots in Figures 14a and 14b are the Boiling Curves with an Oscillation of Amplitude 0.156mm and Five Different Frequencies.

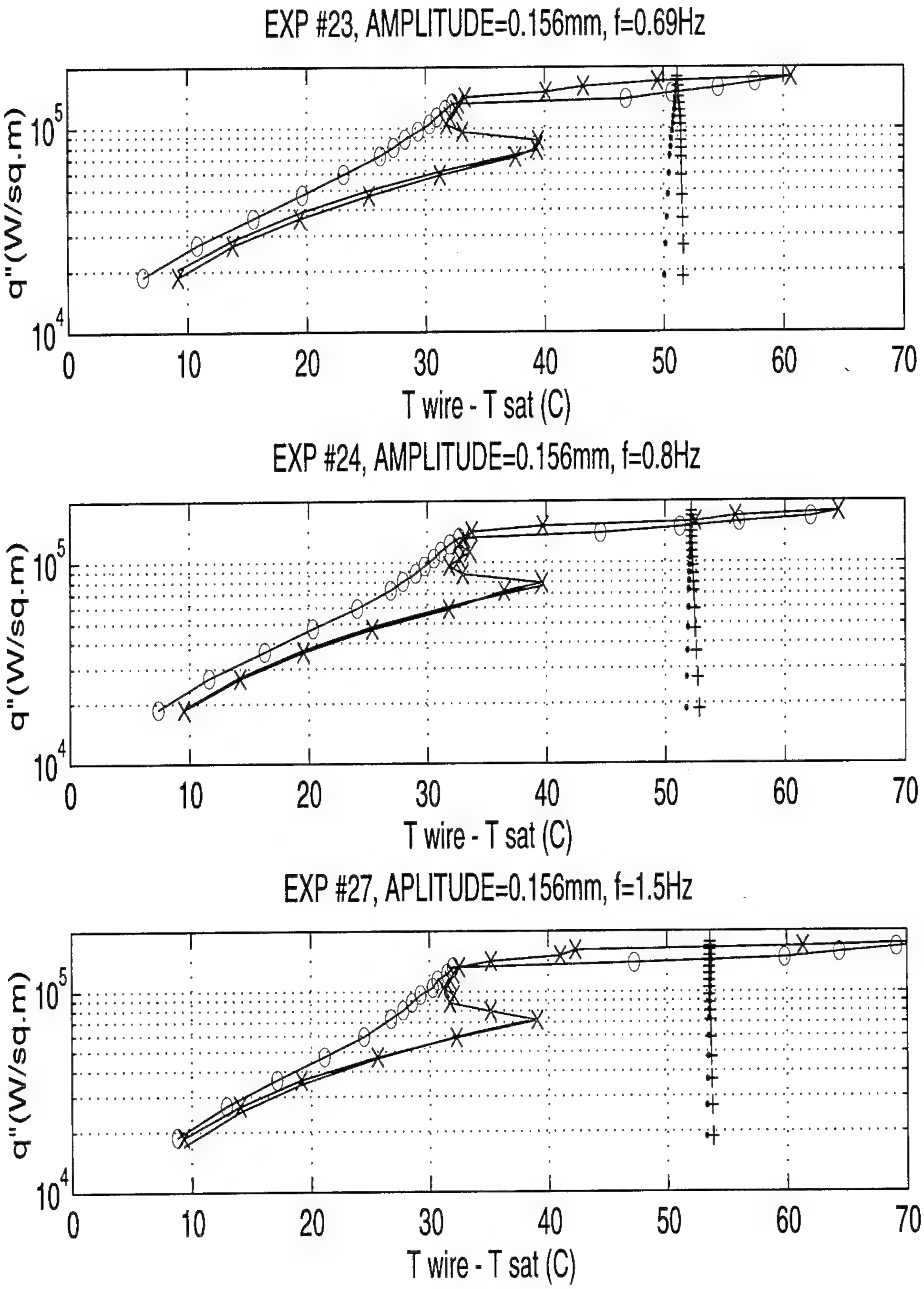

Figure 14b. Top Plot in Figure 14a is the Boiling Curve of FC-72. Other Five Plots in Figures 14a and 14b are the Boiling Curves with an Oscillation of Amplitude 0.156mm and Five Different Frequencies.

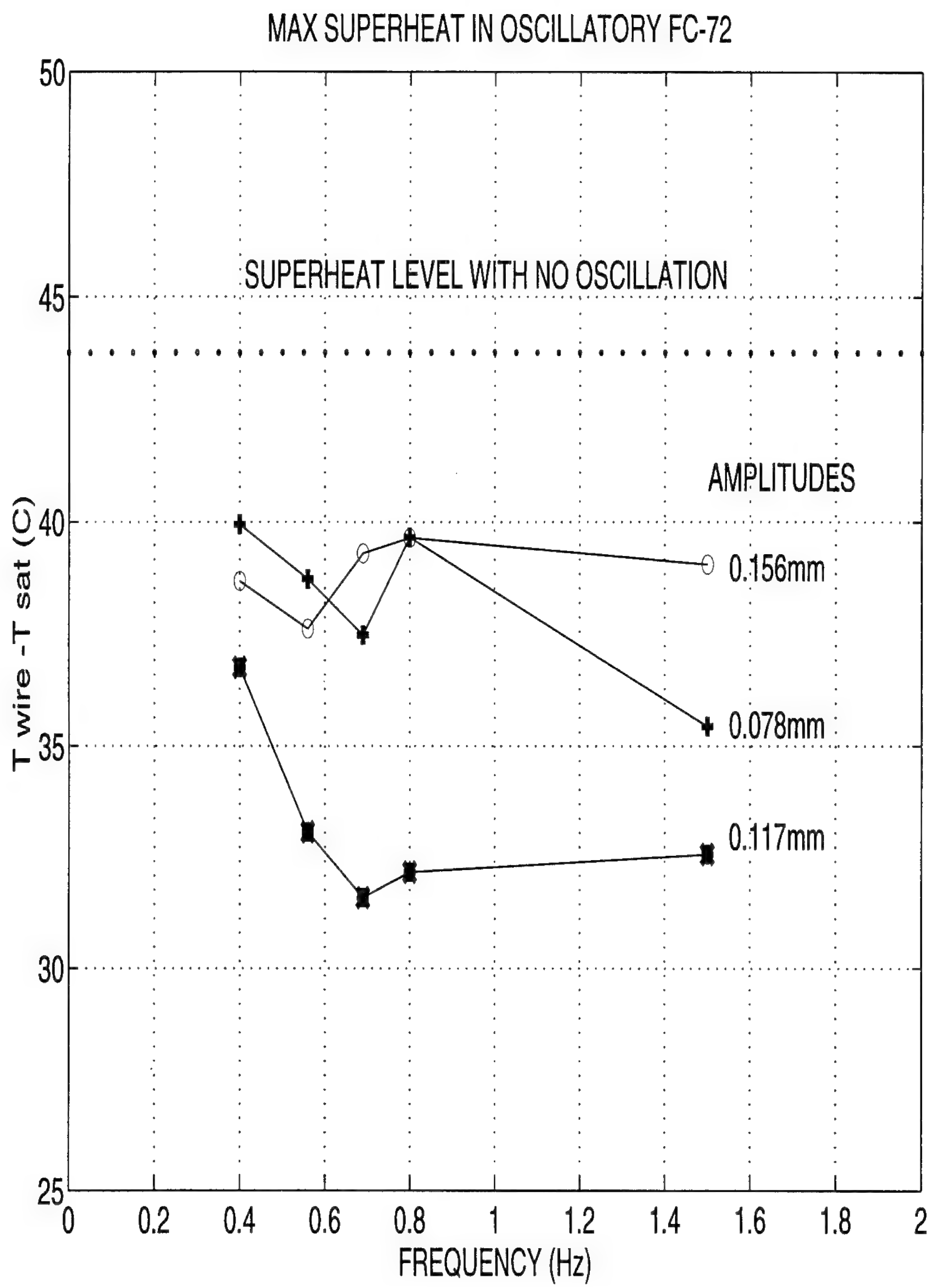

Figure 15. Maximum Temperature OvershootValues Required for the Onset of Nucleate Boiling for Three Different Amplitudes at Given Frequencies are Plotted. It can be Seen That at all Frequencies and Amplitudes There is a Drop in Required Superheat values.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The present study investigated boiling of degassed FC-72 in an oscillating fluid environment. An enhancement of nucleate boiling with oscillation has been confirmed by the results of the experiments. All of the oscillation amplitudes and frequencies changed the boiling curve of highly wetting dielectric fluid FC-72, so that the apparent temperature overshoot in non-oscillating case has decreased. Remarkably at some oscillation amplitude and frequencies the superheat is almost vanished. The amplitude of 0.117 mm and the frequency of 0.69 Hz provided the lowest wall temperature of 87.6 C with 27.7% decrease in the maximum temperature overshoot, which was measured to be 99.7 C for non-oscillating case. In this situation, the boiling incipience took place at the same wall temperature, at which nucleate boiling occurred.

With the decreasing temperature overshoot, the heat flux, at which the incipience of boiling occurs, has dropped, too. On the other hand, critical heat flux has not been effected as much with the oscillation except two cases. At 0.156 mm amplitude and 0.69 Hz and 0.8 Hz, CHF increased from 132,000 W/m^2 up to 142,000 W/m^2.

The other conclusions can be drawn from this study are as follows;

The non-oscillating boiling of degassed FC-72 gave almost identical curves at different runs. At different bulk temperatures, while the natural convection regime remained uneffected, CHF increased with decreasing bulk temperature.

Even though the experiments, which are conducted in this study, proved to be reproducible within the uncertainty limits, in the nucleate boiling phase the wall temperature showed different behaviors as expected.

Here it is possible to conclude that the amount of necessary temperature overshoot for the onset of nucleate boiling, can be decreased with oscillation in the fluid. The reason can be explained by the forces exerted by the oscillating fluid on the bubbles, which are forming on the hot wall. The oscillating fluid can detach the bubbles forming in the

nucleation sites as soon as they start growing on the outer surface. This increases efficiency of nucleation sites, which are very scarce due to the highly wetting dielectric fluid FC-72. It is possible that a nucleation site with increased efficiency can activate other nucleation sites downstream with bubble pumping effect as it has been tested by Kelleher, Egger, Joshi and Lloyd[Ref. 8].

The different effects of the amplitudes and frequencies tested in this study on the boiling curve, is related to the bubble size and growth rate, which depend on the size and shape of the nucleation sites.

B. RECOMMENDATIONS

In this study only three amplitudes and five frequencies are tested. For future research, a more detailed frequency and amplitude map can be created.

With a better SEM technique, the surface of the platinum wire can be examined for the nucleation sites in the right range for boiling of the FC-72.

The experimental setup can be redesign to decrease the oscillation amplitude and frequency uncertainties. It can be done by providing smoother piston operation for example by decreasing friction between the piston and the seal.

The oscillation frequency and amplitude measurement methods can be improved for more accurate readings. If necessary in the future instead of oscillating the fluid, the same sinusoidal motion around the wire can be created by moving the platinum wire or the board mechanically.

The platinum wire board with adjustable spring system can be redesigned to eliminate the difficulties of placing the board into the main chamber. This can be accomplished by providing replaceable power and measurement wires. If the wires are attached to the board at all times, it causes difficulties during handling.

APPENDIX A. CALIBRATION OF PLATINUM WIRE

In this study a platinum wire used as a temperature reading device. The objective of this calibration is to find the relationship between the temperature and the resistance of platinum wire. It is known that the resistance of platinum changes with temperature linearly and the amount of change in resistance can be calibrated to measure temperature.

The method, which used in this study to measure the heat flux from a surface and the surface temperature, has been used by Nikuyama [Ref. 14] in the experiments to determine the boiling regime of water. He used a platinum wire to identify different regimes of pool boiling of water. The temperature of the wire was determined from the knowledge of the manner in which its electrical resistance varied with temperature.

A. SEM ANALYSIS OF PLATINUM WIRE

The platinum wire from the same sample, which is used during the experiments, is analyzed in Scanning Electron Microscope under two magnifications. The magnification of 925x, as it can be seen in Figure 16a, yields that the diameter of the platinum wire is 0.055mm. The magnification of 4930x (Figure 16b) shows the lenghtwise line formations, which have the width of 1-2μm. Possibly these lines formed during the wire drawing process. At the same magnification, it is possible to see 2-3μm diameter bumbs on the surface. No possible nucleation sites are detected at these two magnification.

B. CALIBRATION PROCEDURE IN THE CALIBRATION BATH

During the calibration in the bath following apparatus used:

1. Hewlett Packard 3456A Digital Voltmeter (for 4-wire ohm measurement)
2. Rosemount Engineering Company Model 162C Serial no 985 Platinum Resistance Thermometer (PRT) (to measure the calibration bath temperature. According to Reference 15, PRT has been calibrated in comparison with a platinum resistance temperature standard, which is done by the National Bureau of Standards.)

3. Rosemount Engineering Company Model 920A Commutating Bridge (to measure PRT resistance for temperature measurement)

4. Rosemount Engineering Company Model 913A Calibration Bath (fluid in the bath is ethylene glycol)

5. Rosemount Engineering Company Model 923B Power Supply (to control bath temperature with Neslab Endocal refrigerated circulation bath)

The 0.05 mm platinum wire has been mounted on a plexiglass board and some tension applied by the spring assembly in order to keep the wire straight against thermal expansion. The board immersed into the Rosemount Engineering constant temperature liquid bath. The platinum wire electrically connected to the HP 3456A Digital Voltmeter in the 4-wire Ω measurement arrangement. The bath temperature increased from approximately 25 C to 85 C with the increments of 5 C. When the bath temperature is settled at each setting, the resistance of the platinum wire and the bath temperature recorded. When 85 C is reached, temperature of the bath is decreased down to 25 C with steps of 10 C, in order to detect possible hysteresis in measurements.

The position of the platinum wire in the bath is very important for resistance readings. In the beginning of the calibration, the board placed very close to the surface of the bath and the resistance values on the HP 3456A display were not constant. The board, which holds the platinum wire, immersed into the mid sections of the bath, where the temperature is relatively stable and the platinum wire was next to PRT. The uncertainty of the resistance readings was $\pm 0.001\Omega$.

C. CALIBRATION PROCEDURE IN THE MAIN CHAMBER

After the platinum wire is placed in the main chamber and the chamber is filled with FC-72, another calibration is conducted to check if there is any change in calibration. For the resistance measurements, the platinum wire connected to the HP 3456A Digital Voltmeter in the 4-wire Ω measurement arrangement. The fluid temperature increased from room temperature to the saturation temperature, which is 56 C for FC-72, by the bulk heaters at the bottom of the main chamber. The temperature of the fluid is read by

four thermocouples, which are mounted inside the main chamber by using HP 3497A Data Acquisition/ Control Unit and Unitek desktop computer with a QBASIC code. Randomly the resistance of the platinum wire and the FC-72 temperature recorded.

D. RESULTS AND ERROR ANALYSIS

The calibration data, which is conducted in the calibration bath, can be seen in the first two columns of Table 3 and the top plot in Figure 17. The curve fitting of acquired data resulted the following two linear equations;

$$T = 50.4159 \cdot R - 252.3321 \tag{A1}$$

$$R = 0.0198 \cdot T + 5.0052 \tag{A2}$$

Where: T = Surface Temperature of the Platinum Wire in C.

R = Resistance of the Platinum Wire in Ω

RESISTANCE (ohms)	TEMPERATURE (C)	TEMPERATURE1 (C)	error %
5.4810	23.2700	23.9973	3.0308
5.5980	29.6700	29.8960	0.7558
5.6860	34.2900	34.3326	0.1239
5.8050	40.2600	40.3320	0.1786
5.9010	45.1800	45.1720	0.0178
6.0180	51.0400	51.0706	0.0600
6.1080	55.6000	55.6080	0.0145
6.2150	60.8300	61.0025	0.2828
6.3090	65.5500	65.7416	0.2915
6.4150	70.9700	71.0857	0.1628
6.5240	76.5100	76.5810	0.0928
6.6140	81.0100	81.1185	0.1337
6.7080	85.6700	85.8576	0.2185
6.5110	76.2000	75.9256	0.3614
6.3000	65.5500	65.2879	0.4015
6.1250	56.7100	56.4651	0.4337
5.9110	46.0100	45.6761	0.7310
5.7120	35.9700	35.6434	0.9164
5.5270	26.8200	26.3164	1.9135

Table 3. Calibration Data and Linear Aggression Results.

The linear line in the bottom plot of Figure 17 is this curve fit line. It can be seen how well it matches with the calibration data points. The third column in Table 3 is the temperature values from Equation A1 corresponding to the resistance values in the first column. There is error between the real temperature values and the results of linear aggression. The fourth column in Table 3 is the percent error between the experimental and curve fit temperature values.

In-place calibration check is performed to control the changes in the calibration equation. Tables 4a and 4b are the results of two in-place calibrations. In Figure 18 the two plots are the results of these two in-place calibrations plotted with Equation A1, the calibration curve.

1. The overall average of percent error in temperature calibration is 0.5327%. The average of nominal error between the two temperature values, namely columns 2 and 3, is 0.2056.

2. It is found that the correlation coefficient 'r^2' is 0.9998 for Equation A1.

3. The value of $\sqrt{(1-r^2)} = 0.0145$ indicates that the vertical standard deviation of the data (from precision or random error) is only about 1.45% of the total vertical variation caused by the straight-line relationship between temperature and resistance. Namely, the ratio of the vertical standard deviation of the data about the line to the total vertical variation of data is 1.45%.

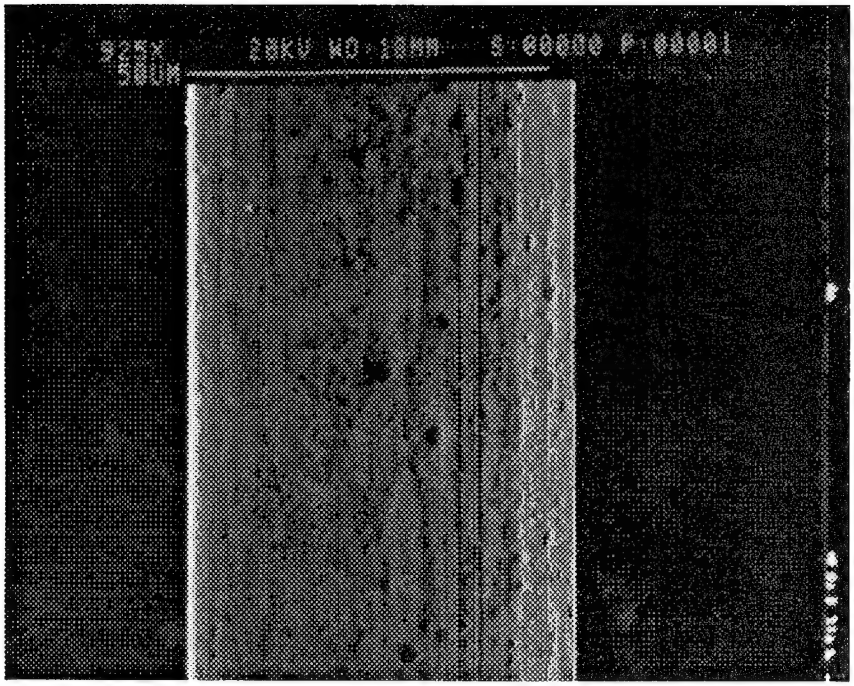

Figure 16a. SEM Picture of Sample Platinum Wire (925x)

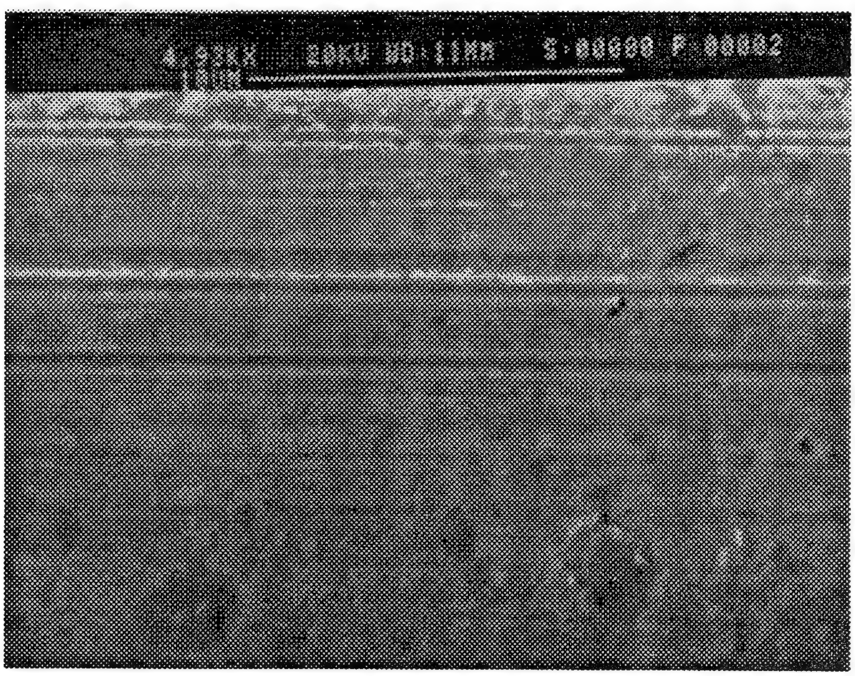

Figure 16b. SEM Picture of Sample Platinum Wire (4930x)

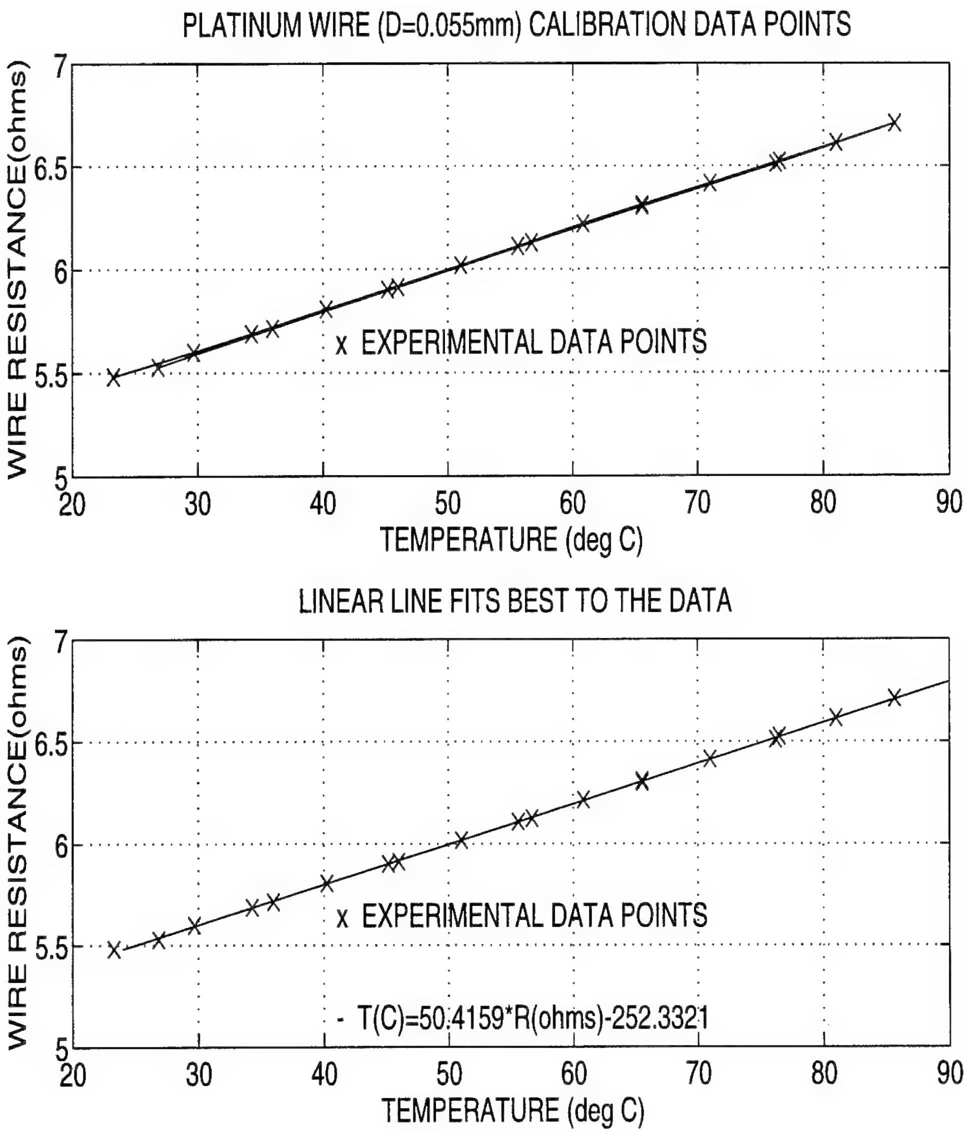

Figure 17. Top Figure is the Data Acquired During the Calibration of Platinum Wire. The Bottom Figure Shows How the Curve Fit Matches to the Experimental Data.

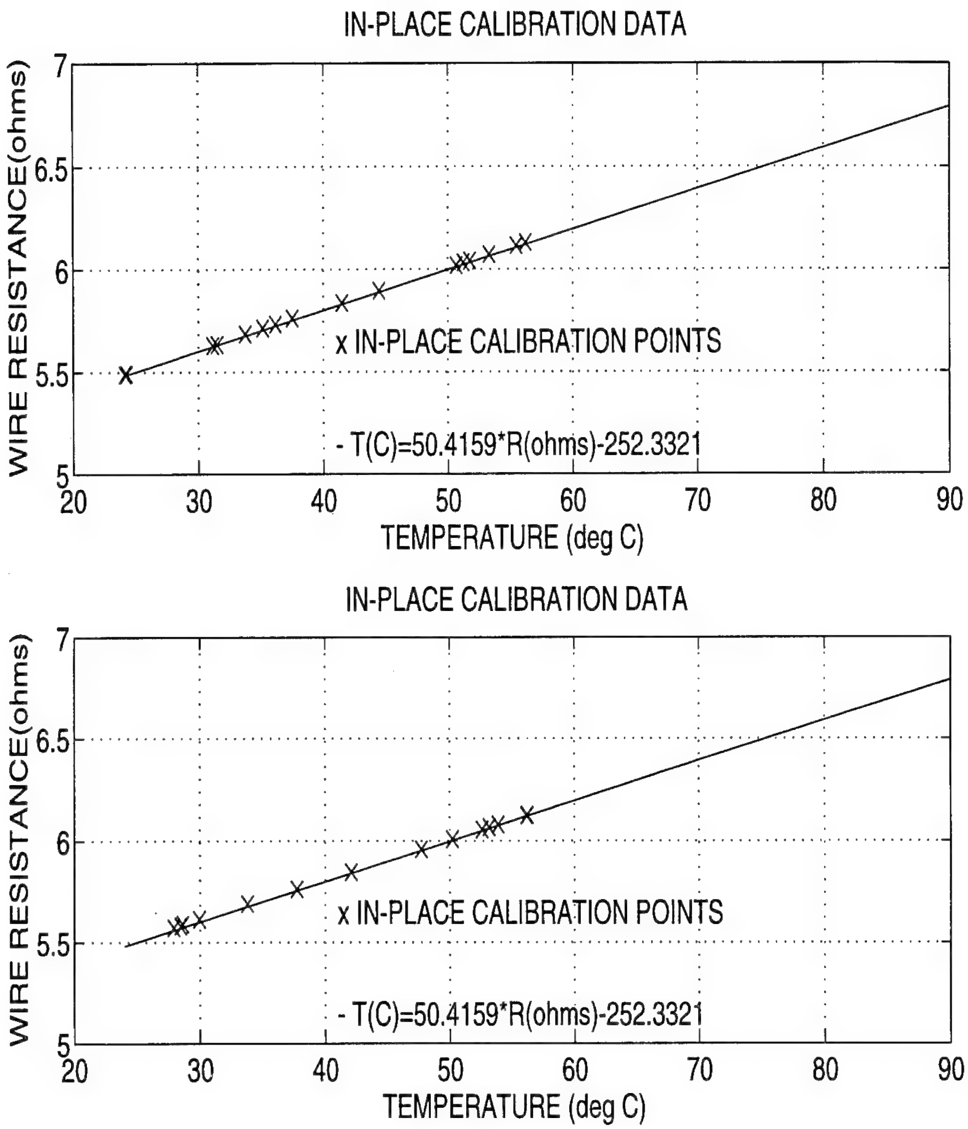

Figure 18. The Data from Two Different In-Place Calibration Comparered to the Curve Fit.

TEMPERATURE (deg C)	RESISTANCE (ohms)
24.2450	5.4900
24.1350	5.4880
31.1400	5.6280
31.4800	5.6340
33.7500	5.6840
35.1400	5.7120
36.1600	5.7310
37.5200	5.7600
41.5100	5.8350
44.4800	5.8940
50.6700	6.0180
51.7700	6.0410
53.3200	6.0720
56.2200	6.1300
55.4900	6.1150
51.2400	6.0320

Table 4a. In-Place Calibration Data #1

TEMPERATURE (deg C)	RESISTANCE (ohms)
27.9040	5.5720
28.4540	5.5800
28.6160	5.5890
29.9420	5.6130
33.7830	5.6890
37.7440	5.7620
42.0970	5.8460
47.7220	5.9580
50.2260	6.0080
52.6040	6.0540
53.1780	6.0660
53.8960	6.0780
56.2070	6.1250
56.2240	6.1240
56.2300	6.1240
56.1840	6.1230
56.1950	6.1230

Table 4b. In-Place Calibration Data #2

APPENDIX B. SAMPLE CALCULATIONS

A. DETERMINATION OF EXPERIMENTAL VALUES

The following sample calculations are the results of 18th experiment, which is at the same time the boiling curve of the FC-72.

1. Condenser temperature:

The condenser temperature is the average of four thermocouple readings, which are embedded in the condenser surface.

$$T_{cond} = \frac{(T_0 + T_1 + T_2 + T_3)}{4}$$

$$T_{cond} = 26.519^\circ \mathrm{C}$$

2. Fluid bulk temperature:

The fluid temperature is the average of four thermocouple readings, which are in the FC-72 medium inside the main chamber

$$T_{bulk} = \frac{(T_4 + T_5 + T_6 + T_7)}{4}$$

$$T_{bulk} = 53.485^\circ \mathrm{C}$$

3. Current of platinum wire and precision resistor:

The current of platinum wire and precision resistor is obtained from the division of voltage drop across the precision resistor divided by its resistance value.

$$I_{Pt.Wire} = I_{2\Omega} = \frac{V_{2\Omega}}{R_{2\Omega}}$$

$$I_{Pt.Wire} = I_{2\Omega} = \frac{0.461}{2.02}$$

$$I_{Pt.Wire} = I_{2\Omega} = 0.2282\mathrm{A}$$

4. Platinum wire resistance value:

The platinum wire resistance is obtained from the division of voltage drop across the platinum wire by platinum wire current.

$$R_{Pt.Wire} = \frac{V_{Pt.Wire}}{I_{Pt.Wire}}$$

$$R_{Pt.Wire} = \frac{1.443}{0.2282}$$

$$R_{Pt.Wire} = 6.3234\Omega$$

5. Platinum wire surface temperature:

To find the platinum wire surface temperature, the calibration formula in the APPENDIX A is used with platinum wire resistance as an input.

$$T_{surf} = 50.4159 \cdot R_{Pt.Wire} - 252.3321$$

$$T_{surf} = 50.4159 \cdot 6.3234 - 252.3321$$

$$T_{surf} = 66.4678^{\circ}\mathrm{C}$$

6. Heat flux from platinum wire:

The heat flux from the platinum wire is equal to the division of electrical power supplied to the platinum wire by the platinum wire surface area.

$$q'' = \frac{I_{Pt.Wire} \cdot V_{Pt.Wire}}{A_{Pt.Wire}}$$

$$q'' = \frac{0.2282 \cdot 1.443}{1.76025 \cdot 10^{-5}}$$

$$q'' = 18{,}707.15\mathrm{W/m^2}$$

where $A_{Pt.Wire} = \pi \cdot L_{Pt.Wire} \cdot D_{Pt.Wire}$

$$A_{Pt.Wire} = \pi \cdot 0.1018736 \cdot 5.5 \cdot 10^{-6}$$

$$A_{Pt.Wire} = 1.76025 \cdot 10^{-5}\,\mathrm{m^2}$$

7. Piston displacement:

The piston displacement is equal to the piston cross sectional area multiplied by the piston stroke length. The following calculations in parts 7 and 8 are done for the stroke length of 1.5 cm.

$$\Delta_{Piston} = \frac{\pi}{4} \cdot D_{Piston}^2 \cdot L_{Stroke}$$

$$\Delta_{Piston} = \frac{\pi}{4} \cdot 0.376^2 \cdot \left(\frac{1.5}{2.54}\right)$$

$$\Delta_{Piston} = 0.06557\text{in}^3 = 1074.5\text{mm}^3$$

8. Amplitude of oscillation in the main chamber:

The amplitude of the oscillation in the main chamber is obtained from the division of piston displacement by the main chamber cross sectional area.

$$A_{Amplitude} = \frac{\Delta_{Piston}}{a \cdot b}$$

where a and b inner length and width of the main chamber respectively.

$$A_{Amplitude} = \frac{0.06557}{5.996 \cdot 2.3377 \cdot}$$

$$A_{Amplitude} = 0.0046\text{in} = 0.117\text{mm}$$

9. Frequency calculation:

The frequency of the oscillation is the arithmetical inverse of oscillation period reading in seconds. The following calculations are done for lowest frequency, which occurs at T=2.5 sec.

$$f = \frac{1}{T_{Period}(\text{s})}$$

$$f = \frac{1}{2.5}$$

$$f = 0.4\text{Hz}$$

B. DETERMINATION OF NUMERICAL VALUES

In this part, natural convection heat transfer around the platinum wire immersed into FC-72 is calculated numerically by using recommended correlation by Kuehn and Goldstein [Ref. 12] and Egger's results [Ref. 13] are used for fluid properties.

1. Film Temperature:

$$T_{film} = \frac{(T_{bulk} + T_{Pt.Wire})}{2.}$$

$$T_{film} = \frac{(53.4293 + 66.4327)}{2.}$$

$$T_{film} = 59.9310^{\circ}\mathrm{C}$$

2. Thermal conductivity:

$$k = \frac{(0.6033 - 0.00115 \cdot T_{film})}{10.}$$

$$k = 0.0534 \mathrm{W/m^{\circ}C}$$

3. Liquid density:

$$\rho_l = (1.740 - 0.00261 \cdot T_{film}) \cdot 1000$$

$$\rho_l = 1.5836 \cdot 10^3 \mathrm{kg/m^3}$$

4. Kinematic viscosity:

$$\nu = 1.203952 \cdot 10^{-8} \cdot \exp\left(\frac{1058.4109}{T_{film} + 273.15}\right)$$

$$\nu = 0.2888 \cdot 10^{-6} \mathrm{m^2/s}$$

5. Specific heat:

$$C_p = (0.241111 + 3.70337 \cdot 10^{-4} \cdot T_{film}) \cdot 4186$$

$$C_p = 1.1022 \cdot 10^3 \mathrm{J/kg^{\circ}C}$$

6. Thermal expansion coefficient:

$$\beta = \frac{0.00261}{(1.740 - 0.00261 \cdot T_{film})}$$

$$\beta = 0.001648 \quad 1/^{\circ}\mathrm{C}$$

7. Thermal diffusivity:

$$\alpha = \frac{k}{\rho \cdot C_p}$$

$$\alpha = 0.3062 \cdot 10^{-7}\,\mathrm{m}^2 / \mathrm{s}$$

8. Prandlt number:

$$\Pr = \frac{\nu}{\alpha}$$

$$\Pr = 9.4339$$

9. Rayleigh number:

$$Ra_D = \frac{g \cdot \beta \cdot (T_{Pt.Wire} - T_{bulk}) \cdot D^3_{Pt.Wire}}{\nu \cdot \alpha}$$

$$Ra_D = 2.9608$$

10. Nusselt number:

$$\overline{Nu}_D = \frac{2}{\log\left[1 + \dfrac{2}{\left[\left(0.518 \cdot Ra_D^{1/4}\left[1 + \left(\dfrac{0.559}{\Pr}\right)^{3/5}\right]^{-5/12}\right)^{15} + \left(0.1 \cdot Ra_D^{1/3}\right)^{15}\right]^{1/15}}\right]}$$

$$\overline{Nu}_D = 1.4036$$

11. Heat Flux

$$q'' = \frac{k \cdot \overline{Nu}_D \cdot \left(T_{Pt.Wire} - T_{bulk}\right)}{D}$$

$$q'' = 19{,}510\mathrm{W} / \mathrm{m}^2$$

APPENDIX C. UNCERTAINTY ANALYSIS

A. UNCERTAINTY IN SURFACE AREA

$D_{Pt.Wire} = 55\mu m = 0.055mm$ Wire Diameter

$L_{Pt.Wire} = 4.011in = 101.88mm$ Wire Length

$\omega_D = 0.002mm$ Uncertainty in Wire Diameter

$\omega_L = 0.06in = 1.524mm$ Uncertainty in Wire Length

$A_{Pt.Wire} = \pi \cdot L_{Pt.Wire} \cdot D_{Pt.Wire}$ Wire Surface Area

$$A_{Pt.Wire} = \pi \cdot 0.10188 \cdot 5.5 \cdot 10^{-6}$$

$$A_{Pt.Wire} = 1.76035 \cdot 10^{-5}\,\mathrm{m}^2$$

$$\frac{\partial A_{Pt.Wire}}{\partial D_{Pt.Wire}} = \left(\pi \cdot L_{Pt.Wire}\right)$$

$$\frac{\partial A_{Pt.Wire}}{\partial L_{Pt.Wire}} = \left(\pi \cdot D_{Pt.Wire}\right)$$

Then the uncertainty in surface area is:

$$\omega_{A,Pt.Wire} = \sqrt{\left(\pi \cdot L_{Pt.Wire} \cdot \omega_D\right)^2 + \left(\pi \cdot D_{Pt.Wire} \cdot \omega_L\right)^2}$$

$$\frac{\omega_{A,Pt.Wire}}{A_{Pt.Wire}} = \sqrt{\left(\frac{\omega_D}{D_{Pt.Wire}}\right)^2 + \left(\frac{\omega_L}{L_{Pt.Wire}}\right)^2}$$

$$\frac{\omega_{A,Pt.Wire}}{A_{Pt.Wire}} = \sqrt{\left(\frac{0.002}{0.055}\right)^2 + \left(\frac{0.06}{4.011}\right)^2}$$

$$\frac{\omega_{A,Pt.Wire}}{A_{Pt.Wire}} = 0.0393 \text{ or } 3.93\%$$

$$\omega_{A,Pt.Wire} = 6.9217 \cdot 10^{-7}\,m^2$$

B. UNCERTAINTY IN POWER

$\omega_{V,2\Omega} = 0.006\%$ Uncertainty in Pre. Res. Vol. Drop [Ref. 11 pp 646]

$\omega_{V,Pt.Wire} = 0.006\%$ Uncertainty in Pt.Wire Voltage Drop [Ref. 11 pp 646]

$\omega_{R,2\Omega} = 0.02\Omega$ Uncertainty in Precision Resistor

$$Q = V_{Pt.Wire} \cdot I_{Pt.Wire}$$

$$Q = V_{Pt.Wire} \cdot \frac{V_{2\Omega}}{R_{2\Omega}}$$

$$\frac{\partial Q}{\partial V_{Pt.Wire}} = \left(\frac{V_{2\Omega}}{R_{2\Omega}}\right)$$

$$\frac{\partial Q}{\partial V_{2\Omega}} = \left(\frac{V_{Pt.Wire}}{R_{2\Omega}}\right)$$

$$\frac{\partial Q}{\partial R_{2\Omega}} = \left(\frac{-V_{Pt.Wire} \cdot V_{2\Omega}}{R^2{}_{2\Omega}}\right)$$

Then the uncertainty in power is:

$$\omega_Q = \sqrt{\left(\frac{V_{2\Omega}}{R_{2\Omega}} \cdot \omega_{V,Pt.Wire}\right)^2 + \left(\frac{V_{Pt.Wire}}{R_{2\Omega}} \cdot \omega_{V,2\Omega}\right)^2 + \left(\frac{-V_{Pt.Wire} \cdot V_{2\Omega}}{R_{2\Omega}} \cdot \omega_{2\Omega}\right)^2}$$

$$\frac{\omega_Q}{Q} = \sqrt{\left(\frac{\omega_{V,Pt.Wire}}{V_{Pt.Wire}}\right)^2 + \left(\frac{\omega_{V,2\Omega}}{V_{2\Omega}}\right)^2 + \left(\frac{\omega_{2\Omega}}{R_{2\Omega}}\right)^2}$$

$$\frac{\omega_Q}{Q} = \sqrt{\left(\frac{0.006\%}{100}\right)^2 + \left(\frac{0.006\%}{100}\right)^2 + \left(\frac{0.02}{2.02}\right)^2}$$

$$\frac{\omega_Q}{Q} = 0.099 \ or \ 0.99\%$$

C. UNCERTAINTY IN HEAT FLUX

$$q'' = \frac{Q}{A}$$

$$\frac{\partial q''}{\partial Q} = \left(\frac{1}{A}\right)$$

$$\frac{\partial q''}{\partial A} = \left(-\frac{Q}{A^2}\right)$$

Then the uncertainty in heat flux is:

$$\omega_{q''} = \sqrt{\left(-\frac{Q}{A^2}\cdot\omega_A\right)^2 + \left(\frac{1}{A}\cdot\omega_Q\right)^2}$$

$$\frac{\omega_{q''}}{q''} = \sqrt{\left(\frac{\omega_A}{A}\right)^2 + \left(\frac{\omega_Q}{Q}\right)^2}$$

$$\frac{\omega_{q''}}{q''} = \sqrt{(0.0393)^2 + (0.0099)^2}$$

$$\frac{\omega_{q''}}{q''} = 0.0405 \textit{ or } 4.05\%$$

D. UNCERTAINTY IN TEMPERATURE

The uncertainty in the thermocouple temperature measurements is the sum of the uncertainties due to the hardware and software, namely HP 3497A and the software used in this study. According to Reference 11, page 650 the temperature measurement accuracy with HP 3497A Data Acquisition/ Control Unit with the HP 3054 A/C Data Acquisition/ Control System Software is ±0.4 C in the temperature range from 0 to 300 C. Even though the software used in this study is different, the accuracy value from the reference book is good enough.

$$\omega_{TC} = 0.4C$$

E. UNCERTAINTY IN WIRE SURFACE TEMPERATURE

As it is given in Appendix A, Section C 'Results and Error Analysis' maximum uncertainty is:

$$\frac{\omega_{Tsurf}}{T_{surf}} = 3.031\%$$

$\omega_{Tsurf} = 0.7273C$ For the surface temperature of 23.27C.

F. UNCERTAINTY IN OSCILLATION AMPLITUDE

$$D_{Piston} = 0.376in$$

$$L_{Stroke} = 10mm$$

$$a = 5.996in$$

$$b = 2.3377in$$

$$\omega_{D,Piston} = 0.005in$$

$$\omega_{L,Piston} = 0.5mm$$

$$\omega_a = 0.01in$$

$$\omega_b = 0.01in$$

$$A_{Amplitude} = \frac{\pi}{4} \cdot \frac{D_{Piston}^2 \cdot L_{Stroke}}{a \cdot b}$$

$$\frac{\partial A_{Amplitude}}{\partial D_{Piston}} = \left(\frac{\pi}{2} \cdot \frac{D_{Piston} \cdot L_{Stroke}}{a \cdot b} \right)$$

$$\frac{\partial A_{Amplitude}}{\partial L_{Piston}} = \left(\frac{\pi}{4} \cdot \frac{D_{Piston}^2}{a \cdot b} \right)$$

$$\frac{\partial A_{Amplitude}}{\partial \mathrm{a}} = \left(\frac{\pi}{4} \cdot \frac{D_{Piston}^2 \cdot L_{Stroke}}{b} \cdot \left(-\frac{1}{a^2} \right) \right)$$

$$\frac{\partial A_{Amplitude}}{\partial \mathrm{b}} = \left(\frac{\pi}{4} \cdot \frac{D_{Piston}^2 \cdot L_{Stroke}}{a} \cdot \left(-\frac{1}{b^2} \right) \right)$$

$$\omega_{A,Amp} = \sqrt{\left(\omega_{DPis} \cdot \frac{\pi}{2} \cdot \frac{D_{Pis} \cdot L_{Str}}{a \cdot b} \right)^2 + \left(\omega_{LPis} \cdot \frac{\pi}{4} \cdot \frac{D_{Pis}^2}{a \cdot b} \right)^2 + \left(\omega_a \cdot \frac{\pi}{4} \cdot \frac{D_{Pis}^2 \cdot L_{Str}}{b} \cdot \left(-\frac{1}{a^2} \right) \right)^2 + \left(\omega_b \cdot \frac{\pi}{4} \cdot \frac{D_{Pis}^2 \cdot L_{Str}}{a} \cdot \left(-\frac{1}{b^2} \right) \right)^2}$$

$$\frac{\omega_{A,Amplitude}}{A_{Amplitude}} = \sqrt{\left(\frac{\omega_{DPiston}}{2 \cdot D_{Piston}}\right)^2 + \left(\frac{\omega_{LStroke}}{L_{Stroke}}\right)^2 + \left(\frac{\omega_a}{a}\right)^2 + \left(\frac{\omega_b}{b}\right)^2}$$

$$\frac{\omega_{A,Amplitude}}{A_{Amplitude}} = \sqrt{\left(\frac{0.005}{2 \cdot 0.376}\right)^2 + \left(\frac{0.5}{10}\right)^2 + \left(\frac{0.01}{5.996}\right)^2 + \left(\frac{0.01}{2.3377}\right)^2}$$

$$\frac{\omega_{A,Amplitude}}{A_{Amplitude}} = 0.0506 \text{ or } 5.06\%$$

G. UNCERTAINTY IN OSCILLATION FREQUENCY

Because of the friction factor uncertainty in the frequency is higher at the lower frequencies.

$$T_{Period} = 2.5s$$

$$\omega_{T,Period} = 0.05s$$

$$f = \frac{1}{T_{Period}}$$

$$\frac{\omega_f}{f} = \frac{\omega_{T,Period}}{T_{Period}}$$

$$\frac{\omega_f}{f} = 0.02 \text{ or } 2\%$$

APPENDIX D. COMPUTER PROGRAMS

A. MAIN DATA ACQUISITION PROGRAM

This QBASIC program executes these operations; To set up communications with HP 3497A and HP 6289A. To control power settings incrementally by the help of HP 59501B Power Supply Programmer. To keep time intervals between steps. To read thermocouple voltages and convert them to temperature values. To make calculations to figure out platinum wire temperature and heat flux. To store temperature and heat flux values in two separate data files.

```
'DATA COLLECTION PROGRAM DURING THE EXPERIMENT

'SET UP COMMUNICATIONS
        OPEN "GPIB0" FOR OUTPUT AS #1
        OPEN "GPIB0" FOR INPUT AS #2
        PRINT #1, "GPIBEOS OUT CR LF"
        PRINT #1, "ABORT"
        PRINT #1, "RESET"
        PRINT #1, "CLEAR"
        PRINT #1, "REMOTE"

STARTIT:
FILEIT:
        PRINT " IF A DATA FILE ALREADY EXISTS WITH THE NAME YOU SELECT, "
        PRINT " PREVIOUS DATA WILL BE OVERWRITTEN  "
        INPUT " ENTER THE NAME OF THE TEMP DATA FILE TO CREATE  ", FILE1$
        IF FILE1$ = "" THEN GOTO FILEIT
        OPEN FILE1$ FOR OUTPUT AS #3
        INPUT " ENTER THE NAME OF THE FLUX DATA FILE TO CREATE  ", FILE2$
        IF FILE2$ = "" THEN GOTO FILEIT
        OPEN FILE2$ FOR OUTPUT AS #4

'BE SURE AT THIS POINT THAT THE FLUID IS DEGASSED AND
'CLOSE TO THE SATURATION TEMPERATURE

     CLS
     VOLTS = 20
     FOR V = 1 TO 18 STEP 1
          IF V < 7 THEN
               VOLTS = VOLTS + 5
          ELSE
               VOLTS = VOLTS + 2.5
          END IF

     VALUE = INT(VOLTS * 10)
     VALUE$ = STR$(VALUE)
     IMAGE$ = "000" + VALUE$                    'CREATE LEADING ZEROS
     VOLTS$ = RIGHT$(IMAGE$, 3)                 'SEND 3 RIGHT JUSTIFIED DIGITS
```

```
    PRINT "COMMAND SENT WAS "; VOLTS$          'SEE WHAT'S GOING OUT
    PRINT ""
    PRINT #1, "OUTPUT 6;2" + VOLTS$            '"2" SETS HIGH RANGE (10 VOLTS)
TIMEPAST = 0
STARTTIME = TIMER
WHILE TIMEPAST < 60                            'DELAY TIME IN SECONDS
    TIMEPAST = TIMER - STARTTIME
WEND
FINISH$ = TIME$

    FOR P = 1 TO 10

' TIME DELAY BETWEEN DATA POINTS
TIMEPAST = 0
STARTTIME = TIMER
WHILE TIMEPAST < 3                             'DELAY TIME IN SECONDS
    TIMEPAST = TIMER - STARTTIME
WEND
FINISH$ = TIME$

' READ VOLTAGES ON PRECISION RESISTOR AND PLATINUM WIRE
    PRINT #1, "OUTPUT 9 ; AR AF20 AL21"        'READ CHANNELS FROM 20 TO 21

  FOR I = 0 TO 1
    PRINT #1, "OUTPUT 9; AS"                   'ANALOG STEP
    PRINT #1, "ENTER 9"
    INPUT #2, DAT$
    VOLT(I) = VAL(DAT$)                        'CONVERT STRING TO NUMBER
  NEXT I
' CALCULATIONS
    VOLT20 = VOLT(0)                           'PRECISION RESISTOR
    VOLT21 = VOLT(1)                           'PLATINUM WIRE
    AMP20 = VOLT20 / 2.02                      'PRECISION RESIS.= 2.02 ohms
    AMP21 = AMP20
    RPLAT = VOLT21 / AMP21
    TPLAT = 50.4159 * RPLAT - 252.3321
    QFLUX = VOLT21 * AMP21 / .000017602529#    'AREA=1.7602529E-5 sq.meter
    TOTALV = VOLT(0) + VOLT(1)

' COLLECT DATA FOR BULK, CONDENSER AND AMBIENT TEMPERATURES
    PRINT #1, "OUTPUT 9; AR AF00 AL08" 'CHANNELS 00 THRU 08

  FOR I = 0 TO 8
    PRINT #1, "OUTPUT 9;AS"                    'ANALOG STEP
    PRINT #1, "ENTER 9"
    INPUT #2, DAT$
    VOL(I) = VAL(DAT$)                         'CONVERT STRING TO NUMBER
    E = VOL(I)
    C(I) = .10086091# * E ^ 0 + 25727.94369# * E ^ 1 - 767345.8295# * E ^ 2 + 78025595.81# * E ^ 3
- 9247486589# * E ^ 4 + 697688000000# * E ^ 5 - 26619200000000# * E ^ 6 + 39407800000000# * E ^
7
```

```
  NEXT I
    AMBI = C(8)
    COND = (C(1) + C(2) + C(3) + C(0)) / 4
    BULK = (C(5) + C(6) + C(7) + C(4)) / 4
    PRINT " BULK TEMP.      = "; BULK
    PRINT " CONDENSER TEMP. = "; COND
    PRINT ""
    DELTAT = TPLAT - BULK
' PRINT DATA TO SCREEN

    PRINT "TIME: "; FINISH$; "  VOLTS= "; VOLTS;
    PRINT "  V=  "; V; "  P=  "; P
    PRINT "TPLAT  = "; TPLAT; "  DELTA T= "; DELTAT; "  TOTAL VOLT = "; TOTALV; "  ";
VOLT21
    PRINT "QFLUX= "; QFLUX
    PRINT ""

' SAVE DATA TO FILE

    PRINT #3, USING "####.###"; BULK; COND; AMBI; DELTAT; TOTALV; VOLT21
    PRINT #4, USING "######.###"; QFLUX
    NEXT P

    NEXT V

    FOR V = 17 TO 1 STEP -1
        IF V > 5 THEN
            VOLTS = VOLTS - 2.5
        ELSE
            VOLTS = VOLTS - 5
        END IF
    VALUE = INT(VOLTS * 10)
    VALUE$ = STR$(VALUE)
    IMAGE$ = "000" + VALUE$                    'CREATE LEADING ZEROS
    VOLTS$ = RIGHT$(IMAGE$, 3)                 'SEND 3 RIGHT JUSTIFIED DIGITS
    PRINT "COMMAND SENT WAS "; VOLTS$          'SEE WHAT'S GOING OUT
    PRINT ""
    PRINT #1, "OUTPUT 6;2" + VOLTS$            '"2" SETS HIGH RANGE (10 VOLTS)
TIMEPAST = 0
STARTTIME = TIMER
WHILE TIMEPAST < 60                            'DELAY TIME IN SECONDS
    TIMEPAST = TIMER - STARTTIME
WEND
FINISH$ = TIME$

    FOR P = 1 TO 10

' TIME DELAY BETWEEN DATA POINTS
TIMEPAST = 0
STARTTIME = TIMER
WHILE TIMEPAST <                               'TIME DELAY IN SECONDS
```

```
    TIMEPAST = TIMER - STARTTIME
WEND
FINISH$ = TIME$
' READ VOLTAGES ON PRECISION RESISTOR AND PLATINUM WIRE
    PRINT #1, "OUTPUT 9 ; AR AF20 AL21"            'READ CHANNELS FROM  20 TO 21

  FOR I = 0 TO 1
    PRINT #1, "OUTPUT 9; AS"                       'ANALOG STEP
    PRINT #1, "ENTER 9"
    INPUT #2, DAT$
    VOLT(I) = VAL(DAT$)                            'CONVERT STRING TO NUMBER
  NEXT I
' CALCULATIONS
    VOLT20 = VOLT(0)                               'PRECISION RESISTOR
    VOLT21 = VOLT(1)                               'PLATINUM WIRE
    AMP20 = VOLT20 / 2.02                          'PRECISION RESIS.= 2.02 ohms
    AMP21 = AMP20
    RPLAT = VOLT21 / AMP21
    TPLAT = 50.4159 * RPLAT - 252.3321
    QFLUX = VOLT21 * AMP21 / .000017602529#        'AREA=1.7602529E-5 sq.meter
    TOTALV = VOLT(0) + VOLT(1)

' COLLECT DATA FOR BULK, CONDENSER AND AMBIENT TEMPERATURES
    PRINT #1, "OUTPUT 9; AR AF00 AL08" 'CHANNELS 00 THRU 08

  FOR I = 0 TO 8
    PRINT #1, "OUTPUT 9;AS"                        'ANALOG STEP
    PRINT #1, "ENTER 9"
    INPUT #2, DAT$
    VOL(I) = VAL(DAT$)                             'CONVERT STRING TO NUMBER
    E = VOL(I)
    C(I) = .10086091# * E ^ 0 + 25727.94369# * E ^ 1 - 767345.8295# * E ^ 2 + 78025595.81# * E ^ 3
- 9247486589# * E ^ 4 + 697688000000# * E ^ 5 - 26619200000000# * E ^ 6 + 394078000000000# * E ^
7
    NEXT I
    AMBI = C(8)
    COND = (C(1) + C(2) + C(3) + C(0)) / 4
    BULK = (C(5) + C(6) + C(7) + C(4)) / 4
    PRINT " BULK TEMP.      = "; BULK
    PRINT " CONDENSER TEMP. = "; COND
    PRINT ""

    DELTAT = TPLAT - BULK

' PRINT DATA TO SCREEN

    PRINT "TIME: "; FINISH$; "  VOLTS= "; VOLTS;
    PRINT "  V=  "; V; "  P=  "; P
    PRINT "TPLAT  = "; TPLAT; "  DELTA T= "; DELTAT; "  TOTAL VOLT = "; TOTALV; "  ";
VOLT21
    PRINT "QFLUX= "; QFLUX
```

```
    PRINT ""

' SAVE DATA TO FILE

    PRINT #3, USING "####.###"; BULK; COND; AMBI; DELTAT; TOTALV; VOLT21
    PRINT #4, USING "######.###"; QFLUX

    NEXT P

    NEXT V

    CLOSE #3
    CLOSE #4

QUES:
    INPUT " DO YOU WISH TO TRY ANOTHER RUN ( Y/N ) ? ", AGAIN$
    IF AGAIN$ = "Y" THEN GOTO STARTIT
    IF AGAIN$ = "y" THEN GOTO STARTIT
    IF AGAIN$ = "N" THEN GOTO ENDIT
    IF AGAIN$ = "n" THEN GOTO ENDIT
    GOTO QUES
ENDIT:
    PRINT #1, "CLEAR "                  'CLEAR ALL INSTRUMENTS ON BUS
    PRINT #1, "LOCAL "                  'PLACE ALL INSTRUMENTS IN LOCAL MODE

    END
```

B. DATA EVALUATION AND PLOTTING CODES

The data stored in two files are plotted by these three MATLAB codes (deney18.m, average.m, kuehn.m) with Kuehn and Goldstein correlation results. Egger's FORTRAN code [Ref. 13, Appendix D] has been used as a model for correlation calculation.

a. Matlab Code 'DENEY18.M'

```
% THIS PROGRAM IS USED IN THE THESIS 'BOILING OF HIGHLY WETTING LIQUIDS IN
% OSCILLATORY FLOW' TO PROCESS AND PLOT EXPERIMENTAL DATA WITH
% FUNCTIONS average(temp,flux) AND kuehn(tbulk,twire)

clear
load temp18
load flux18
temp=temp18;
flux=flux18;

[f,tbulk,twire]=average(temp,flux);

q=kuehn(tbulk,twire);
```

```
dt=twire-56;

semilogy(dt,f,dt(1:18),f(1:18),'x',dt(19:35),f(19:35),'o',dt(1:8,:),q(1:8,:),tbulk(1:18),f(1:18),'+',tbulk(19:35)
,f(19:35),'.');grid
ylabel('HEAT FLUX (W/sq.m)')
xlabel('T wire - T sat (C)')
title('EXP #18, AMPLITUDE=0mm')
axis([0 70 10000 1000000])

print deney18 -deps
```

b. Matlab Code 'AVERAGE.M'

```
% THIS FUNCTION IS USED IN THE THESIS 'BOILING OF HIGHLY WETTING LIQUIDS IN
% OSCILLATORY FLOW' TO AVERAGE EXPERIMENTAL DATA TO BE USED IN
% MAIN MATLAB CODE deney__.m WITH FUNCTION kuehn(tbulk,twire)

function[f,tbulk,twire]=average(temp,flux)

for i=1 :35
ttotal=0;
ftotal=0;
bulktotal=0;
wiretotal=0;
        for j=1:10
                b=(((i-1)*10)+j);
                bulktotal=temp(b,1)+bulktotal;
                wiretotal=temp(b,4)+temp(b,1)+wiretotal;
                ftotal   =flux(b)+ftotal;
        end
tbulk(i)=bulktotal/10;
twire(i)=wiretotal/10;
f(i)=ftotal/10;
end

f=f';                   % heat flux
tbulk=tbulk';           % bulk temp.
twire=twire';           % wire surface temp.
```

c. Matlab Code 'KUEHN.M'

```
% THIS FUNCTION IS USED IN THE THESIS 'BOILING OF HIGHLY WETTING LIQUIDS IN
% OSCILLATORY FLOW' TO CALCULATE NATURAL CONVECTION HEAT TRANSFER
% AROUND PLATINUM WIRE WITH THE CORRELATION RECOMMENDED BY KUEHN
% AND GOLDSTEIN.
% MAIN MATLAB CODE deney__.m USES THIS FUNCTION WITH average(temp,flux)

function[q]=kuehn(tbulk,twire)
```

```
% diameter of the wire (m)

d=50e-6;

% gravitational acceleration (m / sec^2)

g=9.81;

% bulk temperature (C)

tbulk;

% film temperature (C)

tfilm=(tbulk+twire)/2;

% thermal conductivity  (watts/ m . K)

k=(.6033-.00115*tfilm)/10;

% thermal expansion coefficient  (1 / K)

beta=.00261./(1.74 - .00261*tfilm);

% kinematic viscosity of the fluid (sq.m / sec)

nu=1.203952e-8*exp(1058.4109./(tfilm+273.15));

% specific heat of the fluid (J / kg . K)

cp=(.24111+3.70374e-4*tfilm)*4186;

% liquid density of FC-72 (kg / cu.m)

ro=(1.740-.00261*tfilm)*1000;

% thermal diffusivity of the liquid (sq.m / sec)

alfa=k./ro./cp;

% prandlt number of the fluid

Pr= nu ./ alfa;

% rayleigh number of the fluid

Ra=g*beta.*(twire-tbulk).*d^3./(nu.*alfa);

% calculate nusselt number

ter1=(.559./Pr).^(3/5);
```

```
term=(  (.518*Ra.^.25.*(1+ter1).^(-5/12)) .^15 +   (.1*Ra.^(1/3)) .^15        ).^(1/15);
Nu=2./(log(1+(2./term)));

% calculate heat flux (watts / sq.m)

q=k.*Nu.*(twire-tbulk)/d;
```

LIST OF REFERENCES

1. Chu, R.C. and Agonafer, D., *Computer- Aided Thermal Engineering for the Development of Future Electronic Cooling Systems,* Computers and Computing in Heat Transfer Science and Engineering, CRC Press. Inc., pp 409-424, Edted by Wataru Nakayama, and Kwang-tzu Yang, 1993.

2. Scott, A.W., *Cooling of Electronic Equipment,* pp. 4, A Wiley-Interscience Publication, 1974.

3. 3M Corporation, *Fluorinert Electronic Liquids Product Manual,* pp.33, Commercial Chemicals Division, St. Paul, Minnesota, 1987.

4. You, S.M., *Pool Boiling Heat Transfer with Highly-Wetting Dielectric Fluids,* Ph.D. Thesis, Univ. of Minnesota, 1990.

5. You, S.M., Bar-Cohen, A., and Simon, T.W., *Boiling Incipience and Nucleate Boiling Heat Transfer of Highly-Wetting Dielectric Fluids from Electronic Materials,* IEEE Transactions on Components, Hybrids, and Manufacturing Technology, Vol. 13, No. 4, December 1990.

6. You, S.M., Simon, T.W., and Bar-Cohen, A., *A Technique for Enhancing Boiling Heat Transfer with Application to Cooling of Electronic Equipment,* IEEE Transactions on Components, Hybrids, and Manufacturing Technology, Vol. 15, No. 5, October 1992.

7. Marcellus, M.C., Spilhaus, A.F., Jr., and Troeltzsch, L.A., *Heat Transfer Characteristics of Fluorochemical Inert Liquid FC-75,* J. Chem. & Engr. Data, Vol. 6, No. 3, July, 1961.

8. Kelleher, M.D., Egger, R., Joshi, Y., and Lloyd, J.R., *Modification of the Nucleate Boiling Hysteresis in the Pool Boiling of Fluorocarbons,* Heat Transfer 1994, Proceedings of the Tenth International Heat Transfer Conference, Brighton, UK. v. 5, pp. 87-92, Editted by G. F. Hewitt, Published by Institution of Chemical Engineers, Warwickshire, UK, 1994.

9. Melcor Thermoelectrics, *Frigichip Thermoelectric Cooling Devices,* pp. 6, Melcor Corporation, Trenton, New Jersey, Rev. 7/94.

10. 3M Corporation, *Fluorinet Electronic Liquids Product Manual,* Commercial Chemicals Division, St. Paul, Minnesota, 1987.

11. HP 3497A Data Acquisition/ Control Unit *Operating, Programming and Configuration Manual*, Hewlett-Packard Company, December 1982.

12. Kuehn, T.H. and Goldstein, R.J., *Correlating Equations for Natural Convection Heat Transfer Between Horizontal Circular Cylinders,* Int. J. Heat Mass Transfer, Vol. 19, pp.1127-1134, Pergamon Press 1976.

13. Egger, R.A., *Enhancement of Boiling Heat Transfer in Dielectric Fluids*, Master's Thesis, Naval Postgraduate School, Monterey, California, September 1991.

14. Nukiyama,S., *The Maximum and Minimum Values of Heat Transmitted from Metal to Boiling Water Under Atmospheric Pressure*, J. Japan Soc. Mech. Eng.,37,367,1934 (Translation:Int. J. Heat Mass Transfer,9,1419,1966).

15. Rosemount Inc., *Report of Calibration Platinum Resistance Temperature Standard,* Data of Certification by Rosemount Inc., Minneapolis,Minnesota, May 9,1983.

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center 2
   8725 John J. Kingman Rd., STE 0944
   Ft. Belvoir,VA 22060-6218

2. Library, Code 52 2
   Naval Postgraduate School
   Monterey, California 93943-5101

3. Professor M.D. Kelleher 3
   Department Chairman, Code ME
   Naval Postgraduate School
   Monterey, California 93943-5000

4. Naval Engineering Curricular Officer, Code 34 1
   Naval Postgraduate School
   Monterey, California 93943-5000

5. LT. R. A. Egger 1
   4830 Rocky River Drive
   Cleveland, Ohio 44135

6. Deniz Kuvvetleri Komutanligi 4
   Personel ve Egitim Daire Baskanligi
   Bakanliklar / ANKARA - Turkey

7. Istanbul Teknik Universitesi 1
   Makina Muhendisligi Fakultesi
   Isi Transferi Kursusu
   Ayazaga / ISTANBUL - Turkey

8. Bogazici Universitesi 1
   Makina Muhendisligi Fakultesi
   Isi Transferi Kursusu
   ISTANBUL - Turkey

9. Ortadogu Teknik Universitesi 1
   Makina Muhendisligi Fakultesi
   Isi Transferi Kursusu
   ANKARA - Turkey

10. Ugur Turk 2
    Ismet Pasa Mh.
    Nadir Tumer Sk. No=36, 34151
    Bayrampasa / ISTANBUL - Turkey

11. Dr. Dereje Agonafer 1
System 390 Division, IBM Corporation
522 South Rd.,MS P520
Ploughkeepsie, New York 12601-5400

12. Prof. John R. Lloyd 1
Dept. of Mechanical Engineering
Michigan State University
East Lansing, Michigan 48824